6 Soft Robotics: A Developmental Approach

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6.1 Introduction

In this chapter we will first introduce and review soft robotics research, with emphasis on how compliance and softness have changed the robotics landscape in the past two decades. We will then briefly discuss the key ideas in developmental robotics that are fundamental for understanding the relationship between biological and artificial systems, and examine how the developmental sciences and soft robotics are irrevocably linked, into what we have chosen to name "developmental soft robotics." Here, in fact, the two fields can be merged into one in which the developmental sciences can aid in the design and make of soft robots that can then be used as platforms to better understand biological systems. We will finally discuss how phylogenetic development, ontogenetic development, and short-term adaptation are indeed naturally suited to be embedded within a "soft" robotic context. (For further reading, see Trivedi et al. 2008; Pfeifer, Iida, and Lungarella 2014; Laschi et al. 2016.)

6.2 Bioinspired Soft Robotics

Deformation is a fundamental characteristic of biological systems. Almost 90 percent of the human body is composed of soft tissue; many vital organs such as the heart, lungs, muscles, eye lenses, and more depend on deformation of materials.

In bipedal walking, for example, evidence has shown how the soft tissue of the body might not only cushion the impacts of each stride, but also save muscles the effort of actively dissipating energy, while performing a considerable amount of the total positive work, per stride, by soft tissue elastic rebound (Zelik and Kuo 2010).

In the past few decades, there has been an unprecedented advancement in material science and manufacturing techniques, furthering our knowledge of functional materials and empowering artificial systems with newfound capabilities. These advancements, together with a better understanding of biological systems, have given rise to the era of soft robotics, in which bioinspired robotics platforms make use of soft and deformable materials to achieve more flexible, adaptable, and robust behaviors (Kim, Laschi, and Trimmer 2013; Hughes et al. 2016).

Since the dawn of soft robotics, the application of material science and soft-body compliance has changed the robotics landscape. In manipulation, for example, the "universal gripper," a soft gripper capable of particle jamming through vacuum pressure control, has been shown to be able to grasp a large number of objects (Brown et al. 2010). Other solutions for grasping and manipulation range from tentacle-like systems (Laschi et al. 2012) to pneumatic soft grippers (Yap, Ng, and Yeow 2016) and human-inspired soft-robotic hands (Hughes, Maiolino, and Iida 2018; figure 6.1).

Animal-inspired soft robots are among the most developed subareas of soft robotics, where the robot platforms range from worms (Seok et al. 2010) or caterpillars (Lin, Leisk, and Trimmer 2011) to octopuses (Laschi et al. 2012), fish (Katzschmann et al. 2018), and others (figure 6.1). In wormlike soft robots, for example, akin to their biological counterparts, the contraction of longitudinal muscles followed by the contraction of circumferential muscles simulates a traveling wave along the body, generating locomotion (Trueman 1975). In caterpillars, motion is generated by coordinated control of the time and location of the prolegs attachment to the substrate, together with waves of muscular contraction (Belanger and Trimmer 2000).

The ability to mimic these unique systems makes soft robots an exciting new field, where the limits of the (rigid) robots of the past century can be overcome with newfound solutions.

6.2.1 Soft Materials and Soft Actuation

The area of soft robotics is inevitably connected to the field of material science, in which new discoveries in the latter facilitate progress in the former. For a soft robot to be able to use material compliance to aid in robotics tasks, it is necessary for the make of the robot to be, at least in part, deformable. Elastomeric (polymer) materials, like EcoFlex or Drag-

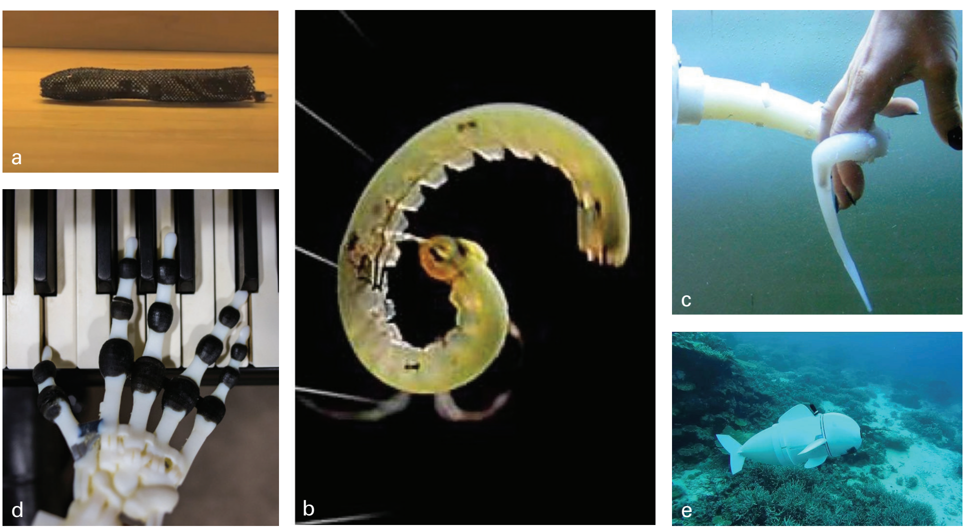

Figure 6.1
Bioinspired soft robot examples. (a) Worm-inspired soft robot. *Source:* Seok et al. 2010. (b) Caterpillar-inspired soft robot. *Source:* Lin et al. 2011. (c) Octopus-inspired tentacle. *Source:* Cianchetti et al. 2011. (d) Human-inspired soft passive hand. *Source:* Hughes et al. 2018. (e) Fish-inspired soft robot. *Source:* Katzschmann et al. 2018.

onSkin (Siegenthaler et al. 2011), have been at the center of researchers' attention for several years, with new substances being discovered every year. Moreover, the advent of three-dimensional printing technology has led to much faster robot design and testing operations than before, facilitating rapid and cheap prototyping in soft robotics.

Actuation poses one of the biggest challenges. In many animals, the coaction of a large number of muscles distributed over the body is capable of generating relatively high forces, facilitating coordinated and robust action. Replicating this ability is no easy feat, as the majority of the robotics solutions lack the ability to generate forces comparable to the industrial robots of the past.

Four main soft-actuation techniques currently exist: tendon driven, pressurized air or fluids, dielectric elastomeric actuators, or DEAs, and shape memory alloys, or SMAs (Kim et al. 2013). First, tendon-driven actuation mimics biological musculoskeletal systems, in which actuation is achieved through the pull and release of tendons, via the appropriate control of motors (figure 6.2*a*). Although a powerful and widespread actuation technique, a large number of tendons are usually necessary to achieve complex behaviors, and control complexity increases along with the number of motors necessary to control the tendons. For softer robots, like continuum soft robots, this type of actuation usually does not scale. Second, the employment of fluids is one of the most powerful actuation techniques for soft robots, capable of generating high forces and displacements. The actuation usually consists of varying the pressure inside predesigned chambers within the body of the robot to achieve their expansion and contraction and generate motion or morphological changes (figure 6.2*b*). However, these actuation systems are usually bulky and heavy and require high power sources, making them unsuitable for untethered robotics systems (Laschi and Cianchetti 2014). Third, DEAs are made of soft materials that can be actuated through electrostatic forces (figure 6.2*c*). DEAs have been shown to have high-strain/stress and mass-specific power. However, the need for DEAs to be prestrained imposes rigid constraints on the robots' design (O'Halloran, O'Malley, and McHugh 2008). Finally, SMAs, with the most common nickel titanium alloys, can generate force through a change in shape due to a rise or fall in the temperature of the material (figure 6.2*d*). Temperature change control, however, is a challenge. High voltages are usually required to achieve temperature changes, and robustness over varying temperatures in the environment is still an issue to be overcome (Rodrigue et al. 2017). Other methods exist; it is possible, for example, to induce pneumatic contraction by evaporating ethanol via resistive heating (Miriyev, Stack, and Lipson 2017) or to achieve bending through combustion (Tolley et al. 2014). Other issues, such as reduced output force or slow speed, however, come into play (Rich, Wood, and Majidi 2018). Soft robotics actuation and material sciences are still an ever-changing field, with new solutions being expedited by fast prototyping and iteration.

6.2.2 Soft Robot Control, Simulation, and Learning

Soft-robotic control poses several challenges and opportunities. Here, the "degree of softness" matters. Take, for example, a rigid robotic hand with the palms and fingertips covered with an elastomeric material. The control of the hand is usually possible to achieve with classical methods (i.e., inverse kinematics), in which the complexity of the control depends on the complexity of the mechanical system. If the hand were entirely rigid, achieving the

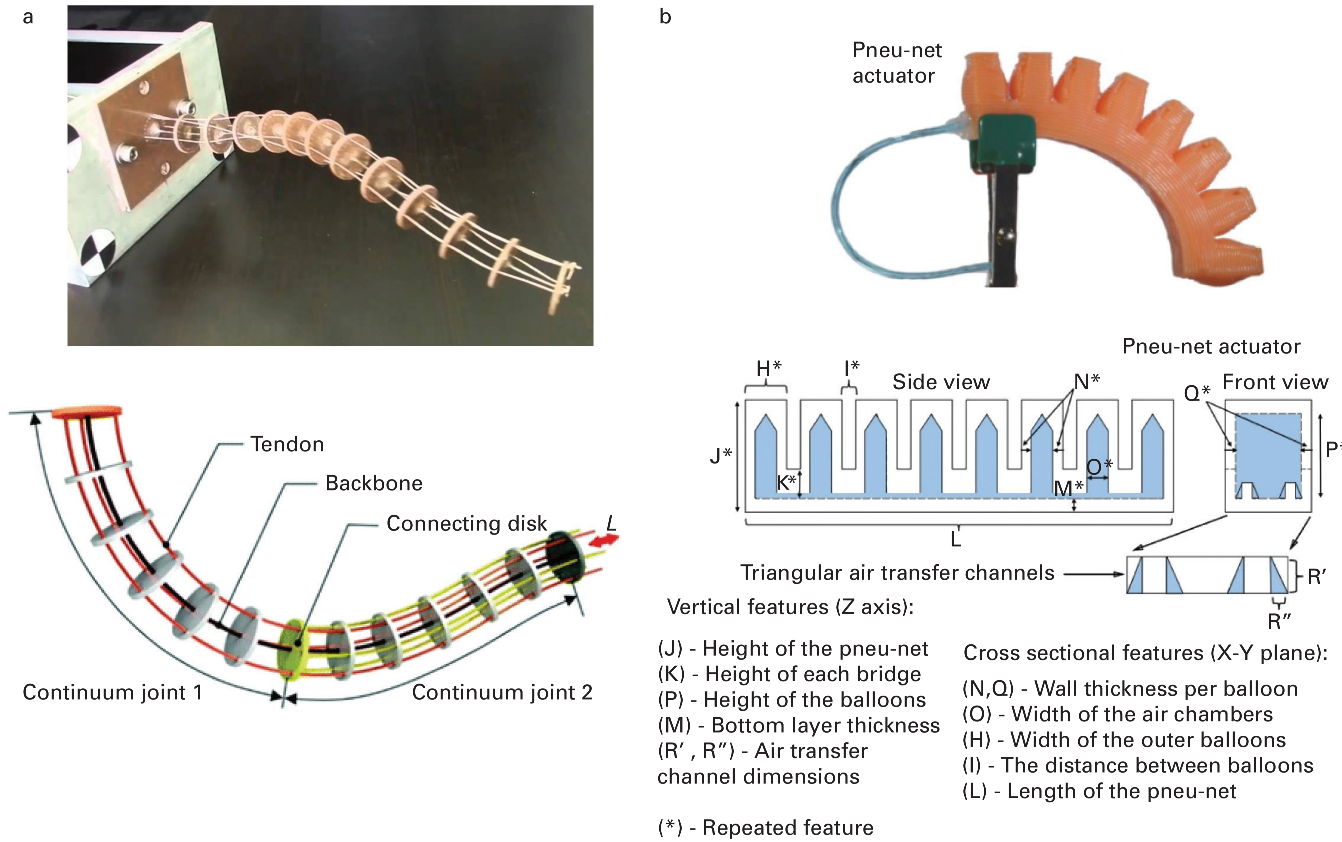

Figure 6.2
Examples of some of the main actuation mechanisms used for soft robotic systems. (a) Tendon-driven continuum robot and model. *Source:* Rucker and Webster 2014; Geng et al. 2018. (b) Pneumatic soft actuator. *Source:* Yirmibesoglu et al. 2018. (c) Variable stiffness dielectric elastomer actuator. *Source:* Shintake et al. 2015. (d) Curved memory alloy–based soft actuator. *Source:* Rodrigue et al. 2017.

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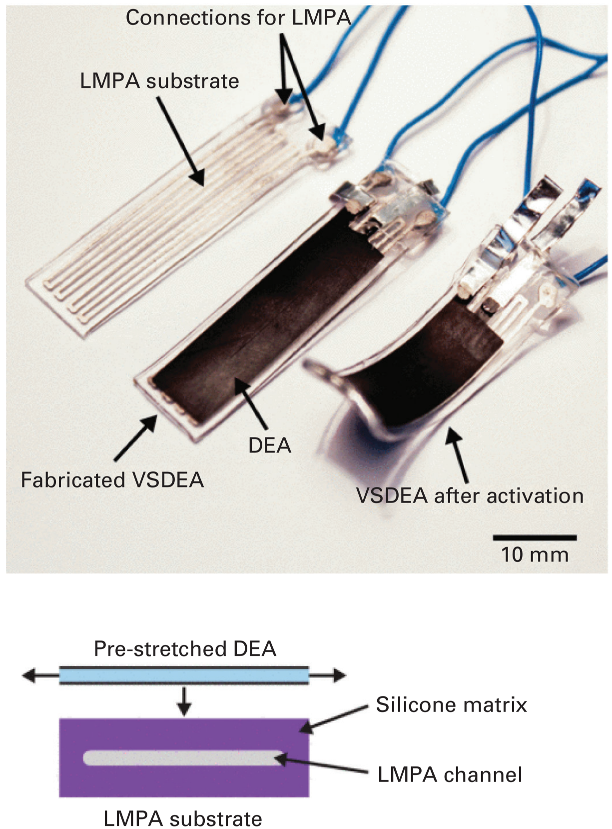

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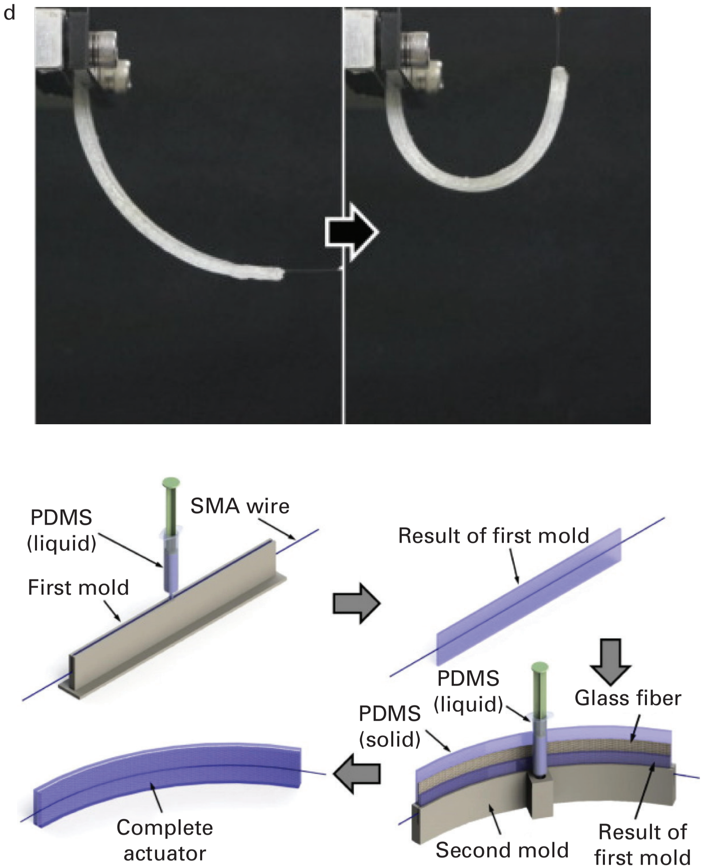

Figure 6.2
(continued)

appropriate control to perform a “light” touch might not be trivial. By appropriately exploiting the mechanical passive dynamics of the soft fingers, the complexity of the control can be reduced to achieve the desired grasping behavior, averting the need for submillimeter precision in robot control (Pfeifer, Lungarella, and Iida 2007; Iida and Laschi 2011). However, as the “degree of softness” in the body increases, new challenges arise.

A robot made entirely of elastomeric materials—for example, one emulating the tentacle of an octopus or the trunk of an elephant—cannot be controlled classically; moreover, proprioception and simulation become problematic. As opposed to the hard links with sliding or rotational joints in classical robots, the continuity and softness of the body makes the control and simulation of continuous soft robots much more difficult. Novel actuation methods aid robotics researchers in their endeavors to achieve desired robot control (section 6.2.1), and new sensing and control methods are discovered on a daily basis (Rus and Tolley 2015). To achieve autonomy and go beyond open-loop control for soft robots, both proprioception and tactile sensing are required.

Much effort has been put into the sensorization of soft robots. The most common soft sensors are perhaps strain sensors, which are soft, deformable sensors capable of sensing body deformations through stretching. It is thus possible to embed such sensors into the (soft) body of a robot without influencing its ability to deform. Some of the most widespread sensors are based on resistive (Homberg et al. 2015) or capacitive (Maiolino et al. 2015) technologies. Recently, work in Galloway et al. (2019) and Scimeca et al. (2019) have shown how it is possible to achieve a high-fidelity proprioceptive understanding of a continuum soft body through sensorization via fiber-optic and capacitive tactile sensors, respectively.

In the context of control and simulation, learning plays a fundamental role. With the infinite degrees of freedom posed by a continuum soft body, for example, precise control via classical methods is hard and usually does not scale. Model-based solutions relying on the piecewise constant curvature assumption have been shown to work for small, tentacle-like robots (Della Santina et al. 2018). However, the error in the controller always increases with an increase in the number of soft segments within the robots. The models, in fact, are usually too simplistic to accurately capture the complexity of continuum soft robots. Learning in this case has been shown to be useful in compensating for a lack of knowledge or model complexity (Scimeca, Maiolino, and Iida 2018, 2020; Rosendo, von Atzigen, and Iida 2017).

6.3 Developmental Soft Robotics

Cognitive developmental robotics (CDR) is an area of research in which robotics and the developmental sciences merge into a unique field, one that seeks to better robotics with insights from developmental sciences and further our understanding of developmental sciences through the use of robotics platforms (Lungarella et al. 2003). The need for CDR to be a research area on its own arose at the dawn of the twenty-first century from the need to understand not only the cognitive and social development of individuals, as explored in the area of epigenetic robotics (Zlatev and Balkenius 2001), but also the acquisition and development of motor skills and how they, as well as morphology, influence the development of higher-order cognitive functions (Lungarella et al. 2003; Asada et al. 2001, 2009).

In this context, robots can be used as experimental subjects, where developmental models can be implemented in robotics platforms, and scientists can gain insights from behavioral analysis, an approach known as synthetic methodology (Scheier and Pfeifer 1999; Sporns 2003).

In stark contrast to the traditional computationalist approach, in developmental robotics there is no clear separation between the physical body, the processes that determine reasoning and decision-making (cognitive structure), and the symbolic representation of entities in the world. Rather, these processes influence each other, and intelligence emerges from their interaction. Developmental robotics is treated in detail in chapter 3.

One of the most difficult tasks in modern-day robotics is to achieve an appropriate robot design for a robot to perform certain tasks in the world. The advent of soft robotics, if anything, has increased the complexity of robots, revoking the rigidity constrains established in the earlier century and bringing about a new era. In this new era, robot design is driven by factors much like biological systems, in which functional morphology, coordinate sensorimotor action, physical adaptation, and embodiment all contribute to the “robot’s survival” in the world and to its ability to see a task to completion.

Developmental soft robotics aims to bring together the areas of soft robotics with those of developmental robotics and the developmental sciences. These, in fact, are irrevocably linked, as we will show.

6.3.1 Soft Robotics and Developmental Timescales

Within the developmental sciences, in its simplest form, the development of a biological organism can be distinguished on three different scales: phylogenetic, ontogenetic, and short-term.

In biological organisms, *phylogenetic development* has the largest timescale, in which changes happen at the level of groups of organisms, over many generations, and processes such as natural selection are responsible for certain “traits” surviving and evolving, while others become extinct. Akin to phylogenetic development is soft robotics design, in which the design of robots is adaptive and ever changing to comply and conform to the task the robot must achieve. Currently, much of the adaptation is due to human design and biased by human skill and experience. However, new methodologies for autonomous designs are a hot research topic, and processes such as evolutionary algorithms have shown promise in the past (Nolfi and Floreano 2000; Doncieux et al. 2015).

Ontogenetic development concerns changes throughout and within the life span of an organism and includes growth and bodily adaptation. The ability of robots to “morph” throughout their life span to achieve desired behaviors has been one of the key advantages of soft robots, as opposed to their rigid counterparts of the previous century. Robots navigating through growth like fungal hyphae (Hawkes et al. 2017), elongating their bodies due to pressure and changing their stiffness to alter their body dynamics and achieve different behaviors (Cianchetti et al. 2013), are examples of such adaptability.

Short-term adaptation refers to the shortest adaptive and developmental timescale of all, in which adaptation needs to be achieved instantaneously. Short-term adaptation is perhaps the most naturally suited to be discussed in a soft setting. In the past this type of adaptation needed to be actively achieved at the control level, where real-time control would allow short-term adaptive behavior through mechanical or sensory feedback. Within the soft robotics framework, much like biological organisms, the short time adaptation is just a consequence of the soft, instantaneous deformation of the soft body itself. When we delicately slide our finger through a ridged surface, for example, the need for complex and precise control is voided by the ability of our dermis to deform and conform to the surface under our touch. Much like the illustrated example, the compliance and softness of materials, in soft robots, can achieve short-term adaptation. The mechanical feedback becomes only a physical consequence of contact, and compliance can naturally suppress the need for complex controllers. Figure 6.3 illustrates the main idea behind the developmental soft robotics framework.

6.3.2 Functional Morphology and Morphological Computation

When designing robotics systems, if shape was initially the most salient of morphological features, with the advent of soft robotics this may no longer be the case. Materials at different levels of elasticity have demonstrated the ability to perform "computation" (Scimeca et al. 2018; Eder, Hisch, and Hauser 2018). Recent work in Scimeca et al. (2018), for example, has shown how complex haptic information can be used to classify objects based on different properties, solely based on clustering analysis. The simplicity of the inference is possible due to a "soft filter" or elastic layer between the tactile sensor and the object. When changing the properties of the elastic layer, the tactile information is appropriately influenced (spatially filtered) in order to induce object similarities with respect to different object properties, like edges or elongation. The "intelligence" is here in the body, since

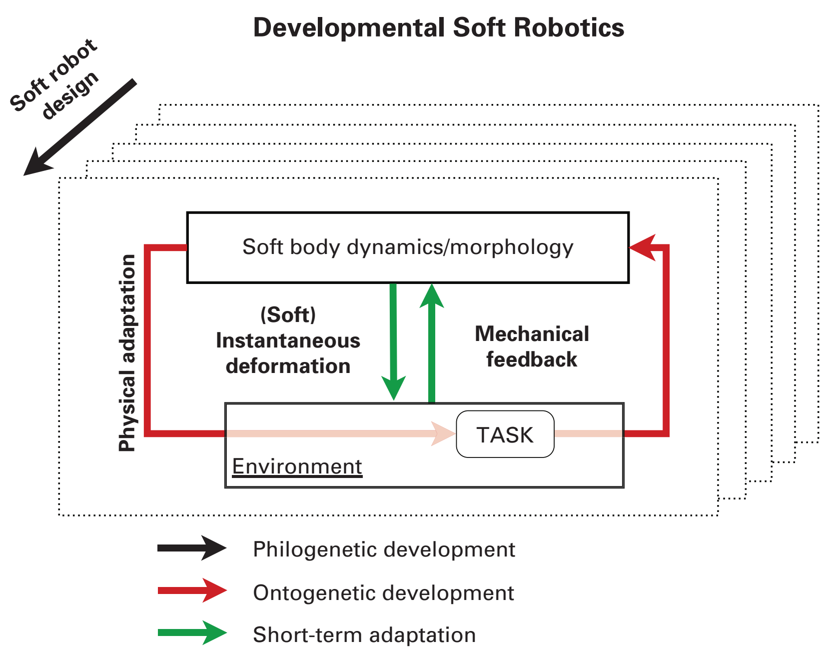

Figure 6.3
Developmental soft robotics.

the body's ability to appropriately mold the sensory information allows for the agent's higher cognitive functions to solve the object classification problem with simple clustering methods, without prior training or supervision, an otherwise impossible feat.

A paradigm trying to make use of the complex body-environment interactions is the "reservoir-computing" framework of computation. The original idea behind reservoir computing begins with network computation, in which an input is fed to a network, which computes a corresponding output. In reservoir computing, a fixed random dynamical system, also known as a reservoir, is used to map input signals to a higher-dimensional space. The "readout" final part of the network, then, is trained to map the signals from the higher-dimensional space to their desired output. As previously mentioned, soft robots, as well as biological organisms, are usually made, at least in part, of soft materials. The body dynamics of soft robots are thus very complex, highly nonlinear, and high dimensional, making control challenging. Through the reservoir-computing paradigm, it is possible to capitalize on the complexity of such a system by exploiting the soft body as a computational resource, using the body dynamics to emulate nonlinear dynamical systems, and, as a result, offloading some of the control to the body itself (Nakajima et al. 2013, 2015). Nakajima et al. (2014), for example, have shown it is possible to control a complex continuum soft arm, inspired by the tentacle of an octopus, in a closed loop without any external controller, by using the body of the robot as a computational resource. In this light, high nonlinearity and complexity may be a desirable property of the body, and design might have to be thought of accordingly.

An additional property that allows soft bodies to be used as a computational resource is memory. The soft body dynamics of soft robots, in fact, can exhibit short-term memory, allowing robots to emulate functions that require embedded memory (Nakajima et al. 2014). When underactuating a continuum soft robot, for example, it may be that the control mechanism is not deterministic with respect to the behavior of the robot. In these cases the behavior of the robot may depend not only on the induced control and its current state but also on the history of the previous robot states, as it may be the case when actuating a soft tentacle arm by moving one of its extremities.

6.3.3 Emergent Behaviors of Soft Robots

At the dawn of the twenty-first century, the concept of "morphofunctional machines" was proposed. Morphofunctional machines were defined as those that were adaptive by being able to change their morphology as they performed tasks in the real world (Hara and Pfeifer 2003). In this context, changes at different timescales were already argued to be important—that is, short-term, ontogenetic, and phylogenetic, or evolutionary. It is important to note that the adaptation and the resolution of the task here is achieved not at the control level but at the morphological level.

As advocated by the developmental robotics paradigm (chapter 3), intelligence and coordinated action are the result of complex interactions between the body, the mind, and the environment. The latter, in fact, plays an important role in determining the behaviors of the artificial or natural organisms living within it.

One of the most influential experiments of the last two decades was the "dead fish experiment," performed in collaboration with Harvard and the Massachusetts Institute of

Technology (MIT) in 2005 (Beal et al. 2006). In the experiment, a dead fish was able to swim upstream even when its brain was clearly sending no control impulse. Upon further study it was apparent how the streamlined body of the fish, passively oscillating, was capable of turning the surrounding energy into mechanical energy and thus propel itself forward passively. Although the morphology and make of the body allowed the dead fish to transduce the surrounding energy, the environment was the enabling factor. The vortices created by water streams were key in the experiment, as they generated the energy to be transduced and recreated the conditions for the body to manifest its propelling abilities. The interaction between the body and the environment were, in fact, the decisive factors in determining the observed behavior. A similar influential experiment was the passive dynamic walker. The make of the robot, with kneecaps, springs, pendulum-like leg swings, and more, was capable of stable, humanlike, and low-energy bipedal locomotion without any complex control. However, the environment initiated and stabilized the walking locomotion, as it manifested when the robot was placed on a downward slope (Collins et al. 2005), allowing the potential energy to be skillfully turned into kinetic energy.

In robot design it is therefore always necessary to take the environment into account. Much like the examples previously mentioned, the body and the brain are often not enough to achieve useful objectives. Things in the world exist to affect and change their surroundings and live within the environment they are situated in (Matarić 2006). In this context it is in the interplay of the body and the environment that intelligent, situated behavior can be observed and that morphology can be empowered and purposefully adapted.

6.3.4 Sensing and Perception of Soft Robots

In nature, morphology plays a fundamental role within the sensing landscape, mechanically converting, filtering, and amplifying sensor stimuli from the outside world to make sense of the surrounding environment or internal states (Towal et al. 2011; Iida and Nurzaman 2016). In rats and mice, for example, vibrissae, or sensitive tactile hairs, have been known to confer to these mammals specialized tactile capabilities, aiding them in a number of sensory discrimination tasks (Prescott et al. 2009). In a similar manner, most mammals have evolved to mediate vision through compound eyes, compromising resolution for larger fields of view and high temporal resolution, and enabling fast panoramic perception (Land and Nilsson 2012). Within the biomimetic robotics field, attempts have been made to endow robotics systems with the capabilities of organisms observed in nature. Haptic robot perception through whiskers (Pearson et al. 2011) and compound vision (Floreano et al. 2013) are two such examples (figure 6.4).

Soft sensing is one of the most popular fields within the soft robotics landscape. Augmenting soft robotics systems with the ability to sense the environment can enable robots to react to unknown events, to improve their control and morphology over time, and to capture information or reason about entities in the world. Sensorizing soft robots is no easy task. One of the goals within this field is to devise sensors that themselves exhibit some “soft” behavioral characteristics; usually, flexibility (i.e., can be bent) and stretchability (Lu and Kim 2014) are desirable. Currently, approaches to achieve stretchable electronics include wavy circuits (Majidi 2014; Rogers, Someya, and Huang 2010) and conductive liquids (Cheng and Wu 2012). One of the most widespread soft sensors are strain sensors, shown to be highly

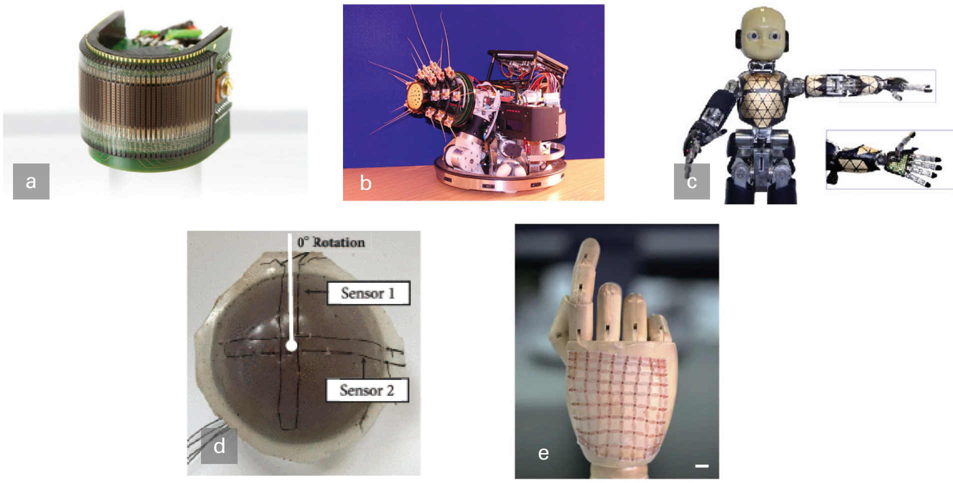

Figure 6.4
Bioinspired flexible and soft sensing examples. (a) Artificial compound eyes. *Source:* Floreano et al. 2013. (b) Robotic tactile vibrissal sensing. *Source:* Pearson et al. 2011. (c) iCub robot with large-area flexible capacitive tactile skin. *Source:* Hoffmann et al. 2017. (d) Conductive thermoplastic elastomer sensorized universal gripper. *Source:* Hughes and Iida 2017. (e) Stretchable and conformable sensor for multinational sensing. *Source:* Hua et al. 2018.

elastic (Muth et al. 2014). New embedding methodologies have also demonstrated the possibility of embedding strain sensors within elastomers through three-dimensional printing techniques. Other flexible sensing technologies such as capacitive tactile sensing (Maiolino et al. 2013) and fiber optics (Galloway et al. 2019) have been used within soft robotics systems.

As previously mentioned, sensorimotor coordination and morphology can enhance the sensing capabilities of robotics systems. Sensors should not be thought of simply as independent and self-sufficient technologies. Instead, it is fundamental to think of sensor technologies as apparatuses that reside within a body. The body dynamics derived from its morphological properties, coupled with the environment the robotic system is situated in, should all contribute to the sensor morphology, its characteristics, and its perceptual capabilities. The appropriate coupling of these factors has been shown to improve the sensing capabilities of robotic systems (Iida and Pfeifer 2006). In Hughes and Iida (2017), for example, the sensorization of a universal gripper was achieved with a pair of conductive thermoplastic elastomer (CTPE) strain sensors (figure 6.4*d*). Differential sensing was then used to compute deformations within the soft body. Morphology, however, was key. By weaving the strain sensor in different patterns within the soft gripper, information regarding the magnitude, orientation, or location of a deformation could be detected. Because such sensing is also inescapably linked to motor control, mechanical dynamics, and the objectives of the robotic system, the concept of "adaptive morphology" has recently been proposed (Iida and Nurzaman 2016), wherein the iterative design, assembly, and evaluation of sensor methologies attempt to explain the adaptive nature of the perceptual abilities of living organisms.

6.3.5 Adaptation and Growth

The principles previously discussed encourage a different approach to design, in line with endowing robots with the ability to adapt to ever-changing environments and indeed make use of the environment as a means of solving their assigned tasks. Besides design principles at a phylogenetic scale and instantaneous deformation on the short-term scale via material properties and design, another important factor is ontogenetic change and adaptation. Plants, for example, are capable of continuously changing their morphology and physiology in response to variability within their environment in order to survive (Mazzolai, Beccai, and Mattoli 2014). Inspired by the unique abilities of plants to survive in diverse and extreme environments, a stream of researchers have more avidly tried to reproduce some of their adaptivity in robotics systems. Plantoids, or robotic systems equipped with the distributed sensing, actuation, and intelligence to perform soil exploration and monitoring tasks, have started to gain traction in this direction (Mazzolai, Beccai, and Mattoli 2014). Rootlike artificial systems in Sadeghi et al. (2013) and (2014), for example, have been shown to be able to perform soil exploration through novel methodologies simulating growth via elongation of the robot's tip. Other plant-inspired technologies in biomimicry and the material sciences include Velcro, from the mechanisms behind the hooks of plant burrs (Velcro SA 1955), bamboo-inspired fibers for structural engineering materials (Li et al. 1995), and novel actuation mechanisms in Taccola et al. (2013) based on reversible adsorption and desorption of environmental humidity and, in Mazzolai et al. (2010), based on the osmotic principle in plants.

Another important factor in ontogenetic adaptivity is the ability of organisms to mend their own tissue over their life spans. Endowing artificial systems with self-healing abilities has recently become of primary importance, setting the landscape for untethered robots to "survive" for longer periods of time in more uncertain and dynamic task environments. Self-healing of soft materials is typically achieved through heat treatment of the damaged areas, which allow some polymers to reconnect and retrieve most of their structural properties. In (Terryn et al. 2017), for example, a soft gripper, a soft hand, and artificial muscles were developed with Diels-Alder materials (Scheltjens et al. 2013). In the developed systems, the Diels-Alder materials were shown to be reversible at temperatures of 80°C, recovering up to 98 to 99 percent of the mechanical properties of the polymers postdamage.

6.3.6 Tool Use and Extended Phenotype

In biology, the phenotype is the set of observable traits of an organism, including its morphology, developmental process, and physiological properties. The idea of extended phenotypes was first introduced by Richard Dawkins (1982) when he argued that the original concept of phenotype might have been too restricted. In fact, the effects that a gene may have are not limited to the organism itself but to the environment the organism is situated in, through that organism's behavior. The coupling of an artificial agent and its environment was discussed in section 6.3.3. The extended phenotype notion, however, extends to even more radical concepts.

One of the most fascinating examples of this is found in primates, corvids, and some fish, which have been found to purposefully make and use "tools" to achieve goals within their environments, such as the acquisition of food and water, defense, recreation, or construction (Shumaker, Walkup, and Beck 2011).

Extending the phenotype concept, the observable traits of the organisms should be augmented to include their extended functionalities, behaviors, and morphology, as derived from the use of the tool in question. When a primate is holding a small branch, for example, the physical characteristics of the primate are undeniably changed: its reach is longer, and its weight and morphology are affected, as is its stance to balance on two or three limbs or its ability to affect the environment around it. Under the extended phenotype concept, these changes must be captured within the phenotypic traits of the organism.

In the context of soft developmental robotics, the ontogenetic development of robotics systems should include their ability to adapt to their environments over their life span (physical adaptation) and indeed their ability to augment their functionality by the active creation and use of tools initially excluded from their phenotypic traits. This ability was previously investigated in Hoffmann et al. (2010) and Nabeshima, Kuniyoshi, and Lungarella (2006), where it was obvious that at the foundation of the idea of tool use was the concept of body schema (cf. chapter 3). The body schema in this scenario requires adaptability and alterability throughout ontogenetic development to cope with the changes in one's body, including growth, as well as with the extended capabilities conferred by the use of tools. An understanding of the tool is necessary here (Wang, Brodbeck, and Iida 2014). Nabeshima, Kuniyoshi, and Lungarella (2006) argued that the temporal integration of multisensory information is a plausible candidate mechanism to explain tool use incorporation within the body schema. Another core component in this context is proprioceptive sensing, or the ability to sense self-movement and body position. Proprioception also plays a significant role in the perception/action model of body representations (de Vignemont 2010).

6.4 Conclusion

Throughout this chapter we have examined the various aspects of bioinspired robotics, with emphasis on soft robotics and the idea that intelligence is exhibited as an interplay, and reciprocal dynamical coupling, of the brain, the body, and the environment. The concept of developmental soft robotics was introduced in this context, in which some design principles can be established on three different timescales, aiding and enabling roboticists and researchers to develop systems for a new generation of robots. Many enabling technologies for sensing and actuation have driven progress in the past few decades and have allowed robots to pass from rigid and industrial to soft and human-friendly. These robots have been shown to achieve locomotion, to pick up and manipulate objects, to safely interact with humans, and much more. However, many challenges still await this field, as the road to the ultimate goal of creating machines with abilities akin to those of organisms in the animal world is only in its early stages.

6.4.1 Physical Soft Robot Evolution

On the phylogenetic timescale, the question of how to achieve complex embodied behavior has been answered by nature for a very long time. The concept of evolution in biological organisms is fairly straightforward, where evolution is thought of as the change in inheritable characteristics of populations over successive generations (Hall and Strickberger, 2008). Due to various sources of genetic variation, new generations have increasingly different traits, and via a mediating process like that of natural selection, some traits will ensure higher or lower chances of survival (Scott-Phillips et al. 2014). Eventually, the surviving population has all the different traits that we can now see in the immense variety of living organisms on our planet, which have adapted to use a plethora of different methodologies and techniques to ensure their survival.

The field of phylogenetics in the context of soft robotics is tightly coupled with this concept, and consequently, this field has a major impact on emergent design and control in robotics. In the area of "evolutionary robotics," evolutionary computation is used to develop physical designs or controllers for robots (cf. chapter 4). Evolutionary computation takes inspiration from biological evolution. In robotics, for example, it is possible to create an initial set of candidate robots and encode their physical and or control characteristics numerically. By testing the robot population against a specific task, it is then possible to identify which combination of morphology and control performed better. The encoded characteristics of the best-performing robots can then be perturbed and used to create a new generation of robots that can be tested again. The iteration of this process for thousands of iterations has been shown to achieve robust controls (Mautner and Belew 2000; Fleming and Purshouse 2002) and designs (Lund, Hallam, and Lee 1997; Lipson and Pollack 2000; Pfeifer, Iida, and Bongard 2005; Vujovic et al. 2017; Brodbeck, Hauser, and Iida 2015).

One of the biggest limitations of evolutionary algorithms lies with the resources and time necessary to achieve good controllers or designs. Because the iteration of robot design, robot testing, and robot evaluation are very time-consuming, it is generally not feasible to apply evolutionary algorithms in very complex problems by starting from a generic, nonbounded, encoding of robot characteristics. The world of simulation has historically been more suited for evolutionary algorithms (Lipson and Pollack 2000; Mautner and Belew 2000; Nolfi et al. 1994) given the ease with which populations can be created, tested, and iterated over. The controllers and designs found, however, are usually not robust real-world solutions, as simulation environments are still very limited, and the solutions found within them do not necessarily correspond to solutions in the real world (Jakobi, Husbands, and Harvey 1995). Moreover, depending on the complexity of the problem, computational resources are still an issue.

In soft robotics, given the complexity of the bodies and the interactions emerging from them, design and control pose two of the biggest problems. Evolutionary algorithms find themselves suited as a candidate solution, but the limitations previously mentioned still apply. Further advancements in virtual reality engines, new manufacturing methods for fast prototyping, advancements in material science, and the ever-increasing power of computing, however, may bypass some of the these limitations in the near future.

6.4.2 Complexity and Scalability

As of today, the robots we see still "feel" unnatural; they move slowly and sluggishly; humanoid robots still do not possess the ability to walk, run, or move the way humans do; they cannot reason about the world the same way we do and they get confused when unknown events occur (Pfeifer, Lungarella, and Iida 2012). One of several reasons contributing to this fact is complexity. The number of actuators and distributed sensors present in humans is much too high to be replicated by motors and standard sensors in machines. This complexity poses a problem, as does controlling the coupling of a high number of motors and sensors. Even when dealing with subproblems, like humanoid hands, the complexity may very well already be too high to try and tackle with standard methods. Some attempts to replicate complexity were made, for example, by replicating in a robotic manipulator many of the degrees of freedom present in a human hand (Tuffield and Elias 2003). This approach, however, did not give the results many were hoping for, as complexity in the body was coupled with complexity in the control, and achieving an adaptable, smooth grasp and manipulation behavior was no easy task. Recent advances have shown how an underactuated, or even passive, hand can achieve complex behaviors, if its interactions with the environment are appropriately exploited (Hughes et al. 2016, 2018). It is here that complexity can be displaced, since complex behavior can emerge from simple design when appropriate interactions take place.

Within this framework, many questions remain. It is, in fact, unclear how design should be achieved to avoid or exploit complexity. Exploiting environmental constraints is no easy feat, as the constraints to be exploited are also tightly coupled with the task at hand. In soft robotics the make of the robots themselves leads to highly nonlinear behaviors and robots with complex dynamics. Paradigms like that of reservoir computing can capitalize on the complexity of such structures, using them as a computational resource and thus making complexity a desirable feature. Control, however, is still hard to achieve, and mathematical models fail to comprehensively account for dynamical interactions when the complexity of the body becomes too high. This complexity presents infinite challenges and opportunities, which the ever-changing landscape of robotics will have to face in the near future.

6.4.3 Learning through the Body

The advancements in artificial intelligence (AI) in the last two decades have begun a scientific revolution, endowing machines with the possibility to achieve superhuman performance levels in several different fields, like image-based object detection (Schmidhuber 2015), virtual agent control (Mnih et al. 2015), and haptic texture identification (Fishel and Loeb 2012). In robotics, machine learning has been extensively used both on the perceptual side, such as for object detection and recognition, and on the control side, such as for robot trajectory planning and motor control.

The most powerful machine-learning algorithms make use of supervision, or the knowledge of target labels, to improve performance over time or trials. Broadly speaking, from the machine-learning point of view, it is common to try to solve a task by fitting a function to sensor or observation data, and thus to try to achieve good performance on the same (or a similar) task when new data is available. The data could, for example, be streaming images from a camera mounted on an indoor mobile robotic platform, and the supervised machine-learning module could learn when and how to turn the wheels left and right, based on collected and labeled visual feeds in a similar indoor environment. Throughout this chapter we have treated the concepts of soft morphology with the repercussions of what are known as morphological processing, sensorimotor coordinated behavior, and soft environment interactions. In similar cases to the example above, it is common for this interconnection of mind, body, and environment to be neglected. In fact, in soft robotics, as well as other robotics areas, the data is usually perceptual information collected by the robot itself. The perceptual information here is influenced by the morphology of the robot's body, as well as the way in which the robot interacts with entities in the world. The soft robot can thus be seen as a reality filter, which can act in its environment and affect the information in the way most appropriate for learning.

Previous research has shown robots to be capable of purposefully affecting the information gathered from their environment through both morphological processing and sensorimotor coordination (Pfeifer and Scheier 1997; Pfeifer, Iida, and Gómez 2006). In this context, not only the information can be structured so it is rendered suitable for learning, but the structure information itself can guide both the morphology and the control of the robot, creating a sensorimotor and morphological adaptation loop capable of intrinsically driving the robot's behavior. We use the term "soft morphological computation" to describe the ability of a soft robot to understand how its own body and actions filter the information retrieved from the world, and change its configuration and interactions accordingly to optimize information retrieval. This simplification can then drive learning and further the adaptive capabilities of autonomous robotics systems. In Scimeca, Maiolino, and Iida (2018), for example, the soft morphology of the robot is shown to be capable of achieving the cluster separation of stimuli belonging to different object types. Learning can therefore be achieved with unsupervised methods, as the "labels" or classes come from skillful body-environment interaction, which induces sensory separation.

The ability of robotics systems to purposefully shape the sensory information through their actions, or morphology, and to learn from the induced structure has the potential to change the learning landscape within robotics systems. In this context, learning may be thought of not as a process that starts in the information world but rather as one that exists in the physical world, where "learning" the actions and interactions appropriate for sensory perception is the first step toward appropriate learning of the sensory stimuli at a later stage.

Additional Reading and Resources

- A comprehensive review of papers on soft robotics (up to 2007): Trivedi, Deepak, Christopher D. Rahn, William M. Kier, and Ian D. Walker. 2008. "Soft Robotics: Biological Inspiration, State of the Art, and Future Research." *Applied Bionics and Biomechanics* 5 (3): 99–117.
- Paper extensively discussing the connection between cognition, body morphology, and material properties: Pfeifer, Rolf, Fumiya Iida, and Max Lungarella. 2014. "Cognition from the Bottom Up: On Biological Inspiration, Body Morphology, and Soft Materials." *Trends in Cognitive Sciences* 18 (8): 404–413.
- Recent overview of current research, technologies, and applications of soft robotics: Laschi, Cecilia, Jonathan Rossiter, Fumiya Iida, Matteo Cianchetti, and Laura Margheri. *Soft Robotics: Trends, Applications and Challenges. Proceedings of the Soft Robotics Week*. Berlin: Springer.
- Soft robotic tool kit website: https://softroboticstoolkit.com.
- Soft robotics TC website: http://softrobotics.org.

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