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Bio-inspired soft robotics: Material selection, actuation, and design

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ABSTRACT

Animals exploit the deformability of soft structures to move efficiently in complex natural environments. These soft structures are inherently compliant and enable large strains in components not typically found in robotics. Such capabilities have inspired robotic engineers to incorporate soft technologies into their designs. One goal in soft robotics is to endow robots with new, bioinspired features that permit morphologically adaptive interactions with unpredictable environments. Here, we review three key elements of bioinspired soft robots from a mechanics vantage point, namely, materials selection, actuation, and design. Soft materials are necessary for safe interaction and overall actuation of bio-inspired robots. The intrinsic properties of materials in soft robots allow for an "embodied intelligence" that can potentially reduce the mechanical and algorithmic complexity in ways not possible with rigid-bodied robots Finally, soft robotics can be combined with tissue engineering and synthetic biology to create bio-hybrid systems with unique sensing, dynamic response, and mobility. Bioinspired soft robots have the ability to also expedite the evolution of co-robots that can safely interact with humans.

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1. Introduction

Bio-inspired soft robots have the potential to match or even exceed the extraordinary versatility and multifunctionality of natural organisms. To achieve this, the design of bio-inspired robots requires tight integration of sensing, passive mechanics, active

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movement, and control. These abilities can be accomplished thro ugh clever integration of soft, rigid, and biological materials into structures that exhibit global compliance and deformability. Prog ress depends not only on the development of new multifunctional materials, but also advancements in 3D manufacturing, robust materials interfacing, and novel systems-level design.

Much of the early effort in soft robotics was motivated by the demand for human-friendly co-robots that could be used for physical human–machine interaction. Applications included pneumatically-powered orthoses for human grasp assistance (e.g. McKibben hand orthotic [1]) and robotic arms for industrial automation (e.g. Rubbertuator [2]). Despite the long history of pneumatic artificial muscles [3], most industrial robots today are motorized or hydraulically driven, and rely on rigid materials for actuation and load bearing. These robots have remained rigid in order to handle heavy objects and perform precise positioning and movement. Unfortunately, these rigidly designed robots can cause additional safety hazards within workplaces, and, as a result, human–robot interactions must be carefully monitored and controlled [4].

While soft robotic advances have been making great strides over the past decade, an area of increasing attention is in soft bio-inspired robotics, which present new opportunities to produce engineered components, devices, and machines that can bridge the gap between conventional robots and natural organisms [5,6]. These new tools could enable seamless interactions between human and robots, and between robots and the natural world. There are many promising applications for soft bio-inspired robots that are biomechanically compatible with humans, including those which address societal needs in healthcare, locomotion strategies, and disaster relief.

Many challenges exist in developing soft bio-inspired robots, including materials, design and system integration. Although some of the engineering principles guiding the development of soft bio-inspired robots are known, new issues can emerge. To produce versatile functionalities of such robots, two objectives should be achieved: (i) replacing modular systems (separate hardware for motor, controller, sensors, etc.) with fully integrated materials architectures that merges these functionalities; and (ii) replacing hard and piecewise rigid mechanisms with soft-matter (e.g. elastomer, gels, fluids, biomatter) that is in physical contact with other objects.

Conventional approaches to address these challenges are not applicable due to soft materials' unique mechanical properties. In contrast to hard bodied robots, soft robots are composed of easily deformable matter such as gels, elastomers, and biological materials that have similar elastic and rheological properties to soft matter found in nature [7,8]. Thus, soft matter engineers require new algorithms to leverage the unique mechanics of these soft components for commercial applications. In this article, we provide a brief review of ongoing efforts to address these challenges in the emerging domain of bio-inspired soft robotics. We begin with an overview of materials typically used to engineer soft robots (Section 2) followed by a discussion of the various approaches for actuation (Section 3). Next, we review several systems-level implementations (Section 4). By gaining insights from the mechanics of how animals use soft materials to adapt to their environment, manipulate objects, and move through terrains, engineers can leverage these capacities to inspire a future generation of robotics.

2. Bio-inspired material selection

To adapt the mechanical versatility and multifunctionality intrinsic to natural organisms, elastic and viscoelastic properties are essential considerations for the material selection of soft robotic components. A number of issues involving the selection of soft materials for soft robots have been raised in other reviews as well [9,10]. In this section useful criteria for materials selection are introduced such as storage and loss modulus as well as work energy density.

Soft components typically used in soft robots include silicone elastomers, urethanes, hydrogels, braided fabrics, hydraulic fluids, and gasses [11]. Elastomers are especially popular since they allow for the utilization of a broad range of desired elastic and viscoelastic properties within the materials architecture of soft robotic devices. These compliant materials also are advantageous when considering the safety of interaction with biological organisms and the overall actuation of soft robots.

Many advantageous traits of soft robots are due to the low stiffness of the materials used to construct them. Conventionally, robotic materials (e.g. metals or hard plastics) have an elastic modulus of 10^9–10^{12} Pa (N/m^2), whereas most materials in natural organisms (e.g. Cartilage, skin, or muscle tissue) have a moduli of 10^2–10^9 Pa [7]. Soft robots can accommodate this elastic property mismatch through mechano-compatibility, through primarily being composed of materials with elastic moduli within the range of biological materials. Typical materials in natural organisms and soft robots tend to deform elastically when a force is applied. Greater compliance allows for a load to be distributed over a larger area, which increases contact time and lowers maximum impact stresses. For instance, due to the conformal nature of soft robots, they can carry or manipulate soft or fragile payloads without causing damage. Popular silicone elastomers that meet the desired compliance matching traits for soft robotic devices include Sylgard 184 and 527 from Dow Chemicals as well as Smooth-Sil 950 and EcoFlex 00-30 from Smooth-On [12]. Soft matter engineering utilize such materials to minimize interfacial stress concentrators between the user and the soft robotic device.

It is important to note that many "soft" materials found in both biology and soft robotics are viscoelastic. The time-dependent viscoelastic properties in biological and soft robotic materials can best be described in terms of their storage and loss moduli, which represent the elastic portion and the viscous portion, respectively (Fig. 1 [11]). Purely elastic materials (e.g. steel, wood, bone) do not dissipate energy when a load is applied and therefore exhibit virtually no loss modulus (which scales with the ratio of loss modulus to storage modulus). In contrast, viscoelastic materials (e.g. muscle, fat, polydimethylsiloxane (PDMS), polyethylene glycol (PEG) Hydrogels, etc.), exhibit both viscous and elastic properties. The inclusion of viscoelastic materials allows for the potential of soft robotic components to dissipate energy and maintain stable motion during dynamical loading. Fig. 1 shows the approximate ranges of storage and loss moduli of several classes of materials, including man-made and natural materials. Fig. 1 depicts which materials are good candidates for various applications for achieving compatibility between different materials in a hybrid system, or avoiding severe stress concentration when using a soft robot.

When selecting materials for a novel soft robot design, it is important to identify optimal viscoelastic material features. Common viscoelastic materials that exhibit elastic hysteresis in soft robotics are urethanes and polyacrylates [13]. Soft polyacrylates like 3M VHB tape are especially popular for dielectric elastomer films, due to their ability to achieve large strains and high electrical field when stretched [14]. Less viscous elastomers like silicone are popular for applications that involve high cycle loading or require high elastic resilience [15]. Another important property of soft, stretchable materials is fracture toughness. Typically, elastic strain limit is sensitive to any features that cause inhomogeneous deformation (e.g. notches, cracks, and other stress concentrators) [16]. Materials that exhibit high fracture toughness include ultratough double network hydrogels that utilize ionically and covalently crosslinked networks to dramatically increase their fracture

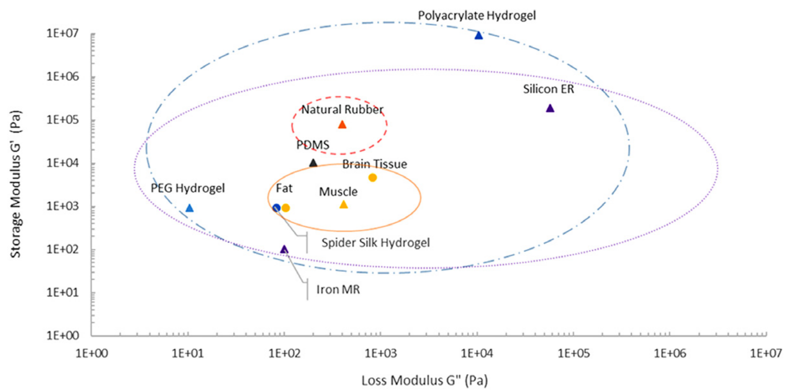

Fig. 1. Approximation of Storage Modulus vs Loss Modulus of various organic and inorganic materials. Hydrogels: -·-·; Biological Tissue: ——; Natural Rubber: - - -; Electrorheological (ER) And Magnetorheological (MR) Fluid Based Polymers: ·······; Materials that have been used in soft robots: Triangle; Hard Materials: Diamond.

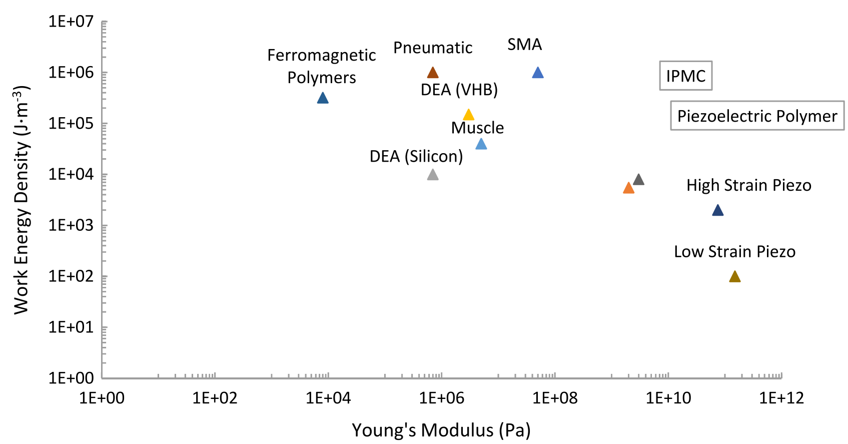

Fig. 2. Work Energy Density vs Young's Modulus of established soft robotic actuator technologies [10,18,19]. Abbreviations: SMA — shape memory alloy, IPMC — ionic polymer-metal composite, DEA — dielectric elastomer.

energies [17]. Integration of these material characteristics aid in the desired actuation capabilities of the robot.

An increasingly important metric that allows for comparison of actuators and materials that meet your design objective is the work energy density. Work energy density, relates the compliance of materials with energy density, by representing the upper bound of elastic energy stored by elastic deformation which are the two pillars of actuated soft system. Work energy density gives an approximation of volume needed of a given actuator technology to accomplish a given amount of work. The higher the energy density of the actuator the less volume needed to meet your design objective. Fig. 2, highlights the tradeoffs between stiffness with the energy density of materials and actuators. Of these actuators the materials used can vastly its change work energy density. Usually stiffer materials have higher energy densities, but are less compliant. Silicone based DEAs have a Young's modulus of 0.1–1.0 MPa and a typical work energy density of 10 kJ m^{-3} [10]. While Acrylic VHB based DEAs have a Young's modulus of 1.0–3.0 MPa and a typical work energy density of 150 kJ m^{-3} [10]. With such a difference in performance characteristics, the most appropriate material and the class of actuators must be considered for a given mechanical task or design objective.

3. Bio-inspired actuation

Conventional robots and soft robots use different mechanisms to achieve actuation. Conventional robots usually have motorized or cable-driven joints that can undergo rotational or translational motions, allowing for finite degrees of freedom for each rigid component. Soft robots have distributed deformations over their soft components allowing for theoretically infinite degrees of freedom [7]. Thus, where rigid robots utilize a motor for every joint, soft robotic actuation is integrated throughout the entirety of the structure. There are several different control methods for soft robotic actuation that utilize these material properties. This includes pneumatics [20–22], electrical actuation [23,24], and chemical stimulation [25,26]. Generally, the actuation of conventional robots is more precise, but soft robotic actuation is more flexible. In this section, we will cover key working principles of soft robotic actuation.

3.1. Variable stiffness

Much like in nature, soft robotic technologies have an intrinsic coupling between stiffness and contraction [27]. For example, muscles exhibit variations in stiffness between their passive (low stiffness) and active (high stiffness) states [28]. Likewise, soft robots utilize similar techniques to apply forces and modulate their load capacity. For example, particle jamming is a technology that allows for variable stiffness of soft robots. One method for achieving this is to fill a thin elastic bladder with filler particles (e.g. beads, coffee grain, dirt, etc.) [6,29]. When a vacuum is applied, the particles pack together and the system transitions from a fluid-like to a solid-like state [29]. Such robotic manipulators can conform to a wide range of 3D shapes and then lock their shape to support a large payload [29]. The onset of rigidity allows for a variable compliance transmission that is useful for gripping [30], bending [29], and locomotion [31].

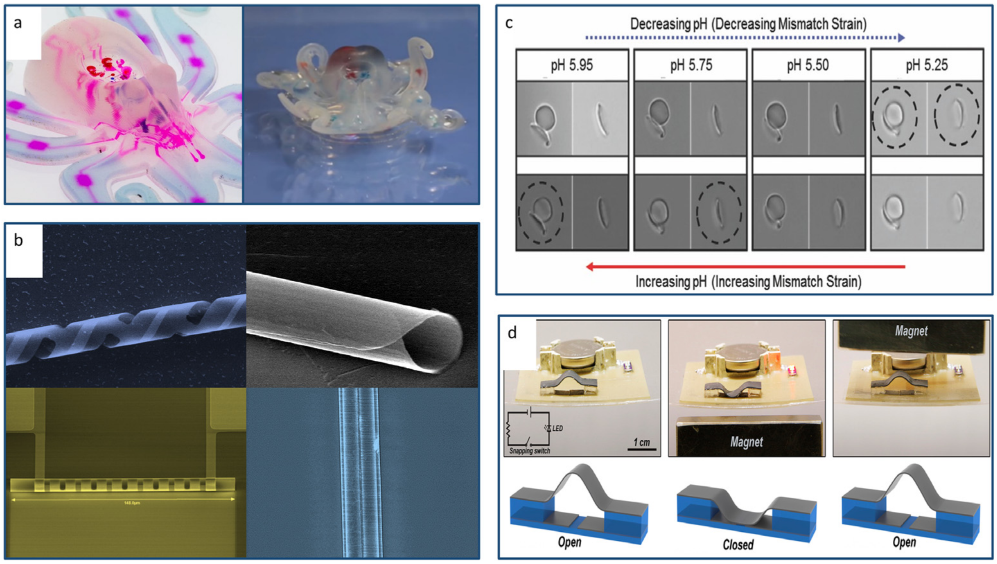

Fig. 3. Soft matter actuation approaches. (a) A pneumatically actuated entirely soft, autonomous robot, inspired by the continuum nature of the octopus, called the 'Octobot' [26], (b) Hierarchical 3D curvilinear structures induced by mismatch straining [32,33], (c) A pH-responsive colloidal particle that rapidly changes shape between two bi-stable geometries [25], (d) A pre-buckled ferroelastomer strip serves as a circuit breaker by exploiting snap-through mechanics in response to a magnetic field [34].

3.2. Mismatch strain

Strain-mismatch is a central principle in the operation of unimorph actuators [35]. Reviews of popular actuation technologies exploiting mismatch strain-induced deformation include dielectric elastomers (DEA's) [13], ionic polymer metal composites (IPMCs) [36], shape memory alloys (SMAs) [37], and biohybrid actuators [38–40]. Mismatch strain-induced deformation refer to the (usually) 3D change of shape in heterogeneous materials that is caused by differential straining in different layers of a component. Such shape changes maybe induced in hard materials such as metals or semi-conducting thin films [41,42], or in soft materials such as PDMS [43], or in hard–soft hybrid systems [44]. Strain induced actuation technologies are highly scalable. Semiconductor micro- and nanotubes have been formed by strain-induced self-rolling of membranes for microelectromechanical systems (Fig. 3(b)) [42,45,33,32]. At the mesoscale, Motala et al. used optical lithography to produce regions of different stiffness's in a PDMS/SU8 sheets which, when submerged in a solvent, underwent a variety of complex programmable folding designs due to differential swelling [43]. DEA's under Maxwell stress are capable both small and large strains [46,47]. Such mismatch strain-induced deformations often lead to 3D curvilinear shape changes, forming, e.g., cylindrical tubes, spherical cups, or wavy edges [43,48]. Sometimes the shape changes are time-dependent, especially if the deformation is induced by chemical processes or governed by diffusion [43,49]. Highly nonlinear processes such as instabilities (to be discussed in more detail below) may also occurs in mismatch strain-induced deformation [44]. All these deformation modes can be utilized to generate actuation in soft robots.

3.3. Elastic instabilities

One challenge for soft robotics is that their actuations are often relatively slow. For fast reconfigurable architectures, soft robotics researchers exploit elastic instabilities. Instabilities in elastic systems cause buckling [50], wrinkling [49], and snap-through behaviors [51]. Such reconfigurable architectures can be ideal for an appropriate response to an external stimulus and there are many ways to release elastic instabilities (e.g. chemically, thermally, magnetically, physically, etc.). One more specific example is based on how the venus fly trap is capable of rapid actuation by the release of elastic instabilities by chemical processes [52]. Inspired by this, Epstein et al. fabricated mechanically, pH-responsive colloidal particles capable of rapid actuation between configurations (Fig. 3(c)) [25]. The bi-stability of the colloidal particles was derived from the colloids' spherical curvature that exhibited a snap through motion. Also, Ramachandran et al. developed a pre-buckled ferroelastomer beam that underwent buckling instabilities in response to an external magnetic field (Fig. 3(d)) [34]. The snap-through mechanics were used to transition between open and closed-circuit configurations. Additional applications of elastic instabilities include programmable origami structures [53] and manipulating fluid flow [54]. Snap-through behaviors in bi-stable or multi-stable structures (i.e., the "jumping" of the structures from one equilibrium configuration to another), are often essential to achieve rapid change of shapes. The switch between stable to unstable configurations offers a lower power, rapid response to desired design objectives.

4. Bio-inspired design

While conventional robots rely on separate modular systems for sensing, actuation, and control, soft robots have the potential to integrate these features into their material architecture. Progress partly depends on new smart materials that allow for an "embodied intelligence". Smart materials couple optimal mechanical properties with desired features, such as programmable stiffness properties, simplified control, proprioceptive sensing, or contact modeling [55,56]. For example, due to their high rigidity, traditional electrical connectors and electrodes are difficult to incorporate into soft structures, so new ways to be both mechanically and electrically coupled are necessary. A promising solution is the inclusion of the liquid metals (e.g. Mercury, Galinstan, EGaIn and liquid silver), to create soft stretchable circuits that remain mechanically intact and electrically functional under extreme elastic deformations [57–59]. Such approaches represent practical methods for the inclusion of flexible sensors, interconnects, transistors, and conductors in soft robots [60,61,59].

Soft robotic actuation is not reliant on discrete joints but instead uses stiffness modulation of soft components (e.g. elastomer, gels, fluids, and biomatter) [6]. Inclusion of such non-rigid materials allows soft robots with continuous systems to exhibit theoretically infinite degrees of freedom. Computer-aided designs (CAD) and virtual models are typically used to assist in the design and actuation behavior of soft robots, but due to nonlinear deformation characteristics of soft components, large deformations are computationally expensive to simulate in real time [62–64]. Therefore, efficient solution techniques continue to be developed for useful coupling of modeling and control of soft robotic systems. One solution which offers useful, accurate control of robots is to couple continuum mechanics with path planning algorithms to allow for modeling reductions [26,65,66]. There is currently no general model to couple continuum mechanics with path planning, so soft robotic engineers often seek inspirations from nature to help inform control mechanisms in their design. In this section, we will elaborate more on bioinspired and biomimetic designs inspired by a range of biological systems.

4.1. Fluidic actuator systems

Flexible fluidic actuators (FFAs) (e.g. Pneumatic artificial muscles (PAMs) [67,68], fluidic elastomer actuators [69], PneuNets [20,21,70], PneuFlex [71]) are driven by compressed air or pressurized fluids to inflate elastomeric materials at positive pressures relative to ambient air [6,72]. FFAs are difficult to model due to the many degrees of freedom that they exemplify and the elastic nonlinearities of their air bladder [73]. FFAs, such as the popular McKibben actuator, informs its actuation behavior similar to the human skeletal muscle system [7]. Skeletal muscles and FFAs are configured in antagonist pairs in order to enable independent control for joint rotation and stiffness [6].

Pneumatic artificial muscles can also be driven by negative pressures. Li et al. developed fluid-driven origami-inspired artificial muscles that utilized an underlying skeletal system to inform actuation behavior [74]. These artificial muscles had an efficiency of about ∼23% and are capable of actuation densities of over 2 KW/kg, which is six times that of mammalian skeletal muscle cells [74]. Despite FFA's being considered to have high work densities, it is important to note that these metrics are much lower when considering external vacuum sources that are typically needed to drive these systems.

FFAs require a power source for actuation, which makes it challenge to create untethered pneumatic robots or systems that are fully soft. Nonetheless, there are recent developments and review articles that address untethered actuation [15,69,76,77], particularly with the inclusion of a combustion chamber to supply pressurized air [78–81]. Combustion powered gas sources can be ideal as they release high amounts of energy and are highly scalable with the size of pneumatic robots. Furthermore, by using onboard control circuits, combustion powered gas sources have been demonstrated to offer high levels of controllability [76]. Notably Wehner et al. utilized microfluidic logic gates as a soft controller of combustion powered gas sources to design an entirely soft, autonomous robot called the 'Octobot' [26]. An entirely soft microfluidic controller was programmed to determine how much aqueous hydrogen peroxide (H_2O_2) would combust and excite the robot's pneumatics, as shown in Fig. 3(a) [26]. The utilization of H_2O_2 as an on-board power source was advantageous due to being a monopropellant with high energy efficiency (1.44 $kJ \cdot g^{-1}$). Desired actuation was the result of the difference in the moduli of the layers within the robot arms. This novel fabrication strategy for entirely soft, autonomous robots will help eliminate external power sources and rigid controllers.

4.2. Bio-inspired robotic implementations

There are many important issues in functional design of a robotic system, such as sensing, actuation, memory, and control. Additionally, design engineers of robotic systems often need to consider more detailed specifications such as the robots' dynamic responses, morphological compatibility, and system-level integration. For soft robotic systems, engineers can take inspirations from nature and integrate many of their design principles into a holistic system.

Much inspiration for soft robotic design comes from the actuation behavior of entirely soft bodied organisms such as earthworms, jellyfish, and octopi. There are plenty of practical engineering designs that can be learned from the octopus's arm due to being a muscular hydrostat [65]. Much like PAM's, the octopus's arm is capable of motion with nearly infinite degrees of freedom. Due to their unique muscular pairing of four groups of the longitudinal (running down the length of the arm) and the radial muscles (perpendicular to the arm axis) (Fig. 4), antagonistic forces enable the octopus arms to elongate, shorten, twist or bend [65,82]. Such organic internal architectures help inform the modeling and design considerations of robots with similar continuum structures [65,66,83]. For example, Kang et al. took inspiration from the hyper redundant motions of octopus's arms to formulate a model of the kinematics and dynamics of a pneumatic manipulator [84]. The modeling of the pneumatic manipulator was greatly simplified with bio-inspired control. In addition, the integration of actuation technologies can be informed by muscle groupings found in nature. Laschi et al. incorporated octopi locomotion strategies by emulating their longitudinal and transverse muscle groupings [23]. Many degrees of motion were achieved by an arrangement of cables longitudinally and shape memory alloy (SMA) muscle groupings transversely (Fig. 4) [23]. SMA's and tendons are popular technologies used to emulate muscular hydrostat locomotion techniques. Other locomotion techniques such as crawling, inching, and jumping of wormlike [85] and caterpillar like robots [24,86] are emulated to inform the design of soft robots.

4.3. Bio-hybrid systems

Engineers exploit features found in nature, not only by mimicking them, but also by interfacing with biological materials [39]. Bio-hybrid robots couple biocompatible synthetic materials with contractile muscle tissues (e.g. smooth, skeletal, and cardiac muscle cells) [87]. With the proper conditions, muscle cells can convert chemical energy into mechanical deformation, locomotion, and control of soft materials with many degrees of freedom [38]. Furthermore, bio-hybrid robots can functionally adapt to their environment, are capable of self-repair and self-assembly, and have developed very sophisticated actuation mechanisms to perform tasks at the micro- and meso-scale [38,40,39]. These advantageous properties have inspired the development of biological machines such as muscular micro-walkers [48,88,89], micro-swimmers [90–93], micro-grippers [48,94], and even self-folding origami structures [95].

As discussed in Section 3.3, bio-hybrid robotic actuation principle revolves around the principle of strain mismatch, similar to the operating principle of thin film actuators. In place of engineered materials such as metal or semi-conducting thin films, contracting cells on the surface of a soft robotic component act as a membrane straining layer [96]. Actuation behavior is determined by the biomaterial composition of the robot. In Fig. 3(b), Nawroth et al. developed an artificial jellyfish that uses a thin layer of cardiac muscle cells to generate the mechanical deformation of a jelly fish [90]. The bending direction of the cell thin-film monolayer was generated by exploiting the ability for cells to self-organize along one direction. Coupling a monolayer of anisotropic cardiomyocytes with an elastomer caused the biohybrid robot to exhibit jellyfish-like kinematics and locomotion (Fig. 5(a)). Notably, the artificial jellyfish is only capable of downward contraction as it swims and

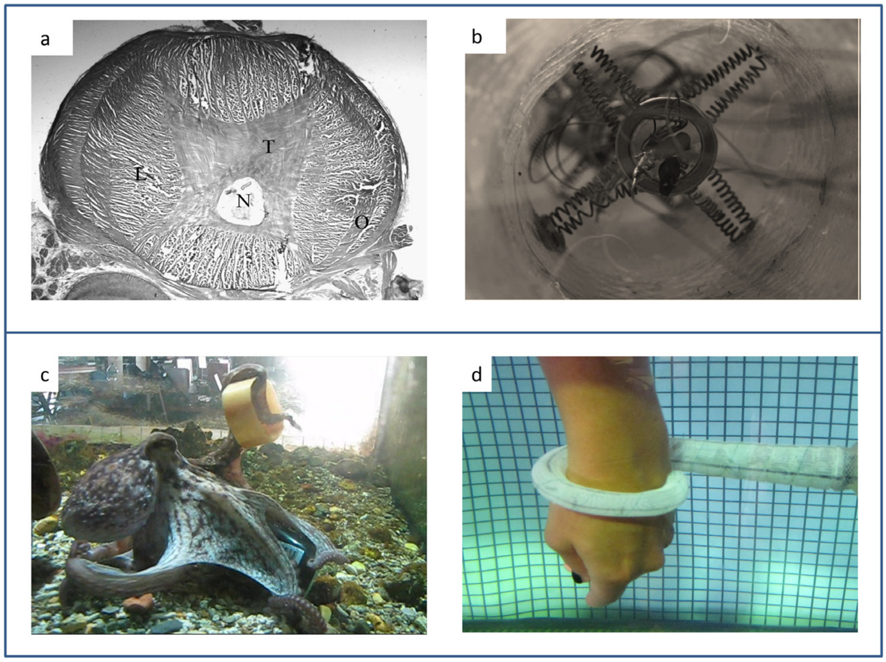

Fig. 4. Bio-inspired design (a) Scheme of the muscle arrangement in the octopus muscular hydrostats: four main longitudinal muscles (L) are arranged along the arm length; transverse muscles (T) are arranged in a radial configuration, along the central channel, containing nervous fibers (N), with fibers interspersed within the longitudinal muscles; oblique muscles (O) [23], (b) Arrangement of transverse SMA actuators mimicking octopus transverse muscle with longitudinal tendons emulating longitudinal muscles [23], (c) Octopus vulgaris, the animal often used to inform the design of octopus-like robots [75], (d) Octopus-like manipulator wrapping itself around a human hand [23].

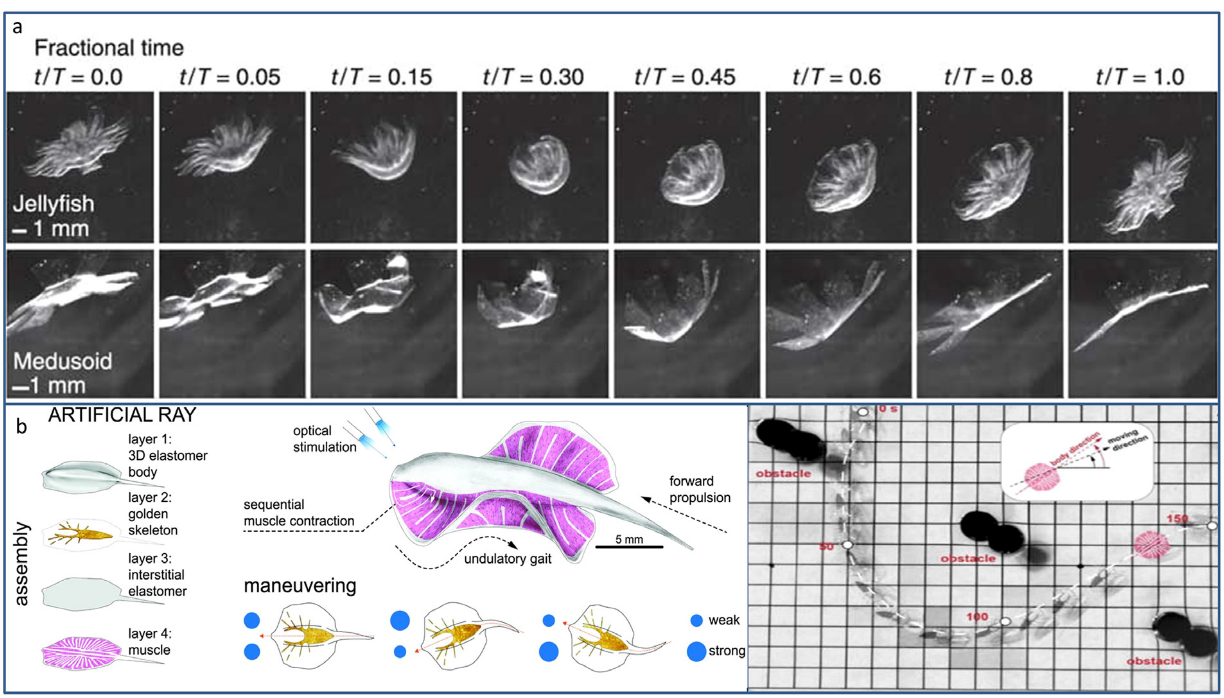

Fig. 5. Biohybrid muscle cell based actuators (a) Time lapse of stroke cycle in jellyfish (top) and an artificial jellyfish (bottom) [90], (b) (left) A biohybrid assembly components that mimics the actuation behavior of a sting ray, (b) (right) Soft artificial ray navigates through an obstacle course [93].

is therefore limited by the drag of its rebound stroke. Upward contraction against the drag would require an additional layer that can act antagonistically to the muscular thin film. A notable improvement of the design of the bio-hybrid robot comes from a tissue-engineered ray (Fig. 5(b)). Unlike the jellyfish that is composed of two layers (PDMS and rat cardiomyocytes), Park et al. improved the design of an artificial sting ray that had four total layers. The artificial sting ray contains a skeleton structure that stores elastic energy during the down stroke of the muscle layer and releases that energy against drag during the subsequent muscle relaxation

Table A.1
Sources of materials properties used in Fig. 1.

Polydimethylsiloxane (PDMS)	[100]	Brain tissue	[101,102]	MR fluids	[103]
ER Fluid based polymers	[104]	Muscle tissue	[105–107]	Porcine fat	[108]
DF-PEG hydrogels	[109]	Spider silk hydrogel	[110]	Chitosan/ polyvinyl hydrogel	[111]
Polyacrylate hydrogel	[112]	Natural rubber	[113]		

Table B.2
Sources of material properties in Fig. 2.

DEA (VHB)	[10]	Pneumatic	[19]	Ferromagnetic polymers	[10]
DEA (silicon)	[10,114]	Muscle	[10]	Piezoelectric polymer	[19,114]
SMA	[10,19]	IPMC	[10]	Hydraulic	[19]

phase [97]. Phototactically stimulated contraction of serpentine rat cardiomyocytes patterns lead to coordinated swimming of the robot that emulates sting ray locomotion [97]. Such bio-hybrid robot design improvements allow for a dynamic level of control that had not been achieved before, as was demonstrated by the soft robot navigating through an obstacle course (Fig. 5(b)).

5. Concluding remarks

In this mini-review article, we discuss the nascent field of bio-inspired soft robots. We focused on how biology can help inform the advancement of three essential topics within the field: material selection, actuation, and design. First, we discussed which mechanical properties are essential considerations for the material selection of soft robotic components. We then reviewed several of the actuation technologies used to leverage these mechanical properties. Lastly, we enumerated several of the soft bodied systems that we believe strongly influence later developments.

To achieve the full potential of soft robots, there is much work that must be done to address the numerous key challenges that lie ahead. The core of these challenges revolves around understanding of the structure–property relations of soft robotic components that aid in the design objectives of soft robots. Coupling features with design objectives requires new smart materials. Also, due to the amorphous nature of soft components, there is no current standardization of soft robotic design. Ideally, a catalog of well-defined materials and design architectures would enable soft matter engineers to build upon requisite work instead of applying abstractions of soft design principles.

High quality standardization of active materials for the well accepted reliable fabrication paradigms will promote robust scalable mass production of complex soft actuators. For example, Zhao et al. have developed a design and manufacturing technique to fabricate wearable assistive devices [98]. The article illuminated several relevant elements to its fabrication process: material properties (viscosity, elastic modulus, ultimate strength, and elongation), modes of failure, and possible improvements to its design. Such methods increase the accessibility of these approaches by experts in other fields (e.g. additive manufacturing, biomedical engineering, control engineering, simulation experts) to learn from and further advance the field of soft robotics.

As soft robotic systems are better understood, there will be a fusion of conventional robots and soft robots working seamlessly in the same environment. Dexterous soft graspers have already made their debut in manufacturing plants, as companies like Soft Robotics Inc. have PnueNet actuators in use for grasping soft food items. In addition, there will also greater integration of soft robots into human lives. Soft technologies allow for safer interactions that are otherwise not available with conventional robots and their adaptive behavior will simplify the controllers necessary to facilitate physical interaction.

Topics not covered in the current mini-review include the robots' ability to memorize and ability to learn, i.e., empowering the soft robots with artificial intelligence (AI). Some of these AI capabilities are already implemented in conventional robots, such as in driverless cars and robotic personal assistants. However, as pointed out by Tegmark [99], these functions of robots are independent of physical substrates (platforms). Although the efficiency of accomplishing these functions may be different on different platforms, the principles of running AI on them are the same. The algorithms used in conventional, hard-bodied robots can be implemented in soft robots have the potential to be extremely useful and effective.

The variety of applications of soft robots will further converge disparate technologies for novel applications. As scientific concepts and novel technologies contribute to soft robots' potential in many real life applications, we will further see soft robots used for medical applications, field operations, and manufacturing. Ultimately, we envision that soft robotic technologies will become common within the industrial, healthcare, educational, and consumer space.

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Appendix A

See Table A.1.

Appendix B

See Table B.2.

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