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TOPICAL REVIEW

What is an artificial muscle? A comparison of soft actuators to biological muscles

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Abstract

Interest in emulating the properties of biological muscles that allow for fast adaptability and control in unstructured environments has motivated researchers to develop new soft actuators, often referred to as 'artificial muscles'. The field of soft robotics is evolving rapidly as new soft actuator designs are published every year. In parallel, recent studies have also provided new insights for understanding biological muscles as 'active' materials whose tunable properties allow them to adapt rapidly to external perturbations. This work presents a comparative study of biological muscles and soft actuators, focusing on those properties that make biological muscles highly adaptable systems. In doing so, we briefly review the latest soft actuation technologies, their actuation mechanisms, and advantages and disadvantages from an operational perspective. Next, we review the latest advances in understanding biological muscles. This presents insight into muscle architecture, the actuation mechanism, and modeling, but more importantly, it provides an understanding of the properties that contribute to adaptability and control. Finally, we conduct a comparative study of biological muscles and soft actuators. Here, we present the accomplishments of each soft actuation technology, the remaining challenges, and future directions. Additionally, this comparative study contributes to providing further insight on soft robotic terms, such as biomimetic actuators, artificial muscles, and conceptualizing a higher level of performance actuator named artificial supermuscle. In conclusion, while soft actuators often have performance metrics such as specific power, efficiency, response time, and others similar to those in muscles, significant challenges remain when finding suitable substitutes for biological muscles, in terms of other factors such as control strategies, onboard energy integration, and thermoregulation.

Glossary of terms and definitions

Actuator efficiency: the energy conversion efficiency between the energy activation driver input and the mechanical work output ignoring elastic strain and/or electrostatic energy.

Adaptive dynamic response: the ability of an actuator to actively change its inherent stiffness/compliance, damping, or both in order to adjust its time-variant dynamics.

Embedded control: actuator level sensing and feedback control, excluding supervisory controller (brain, etc).

Integration: the capacity to merge actuation elements like onboard energy source and sensor in the actuator's architecture.

Lifetime: the maximum number of actuation cycles that a soft actuator or a biological muscle can perform without failure or degradation.

Maximum actuation strain: the maximum deformation that an actuator is capable of performing divided by the initial length of the actuator, usually measured under non-loaded conditions.

Maximum actuation stress: the maximum stress that an actuator is capable of performing divided by the cross section area of the actuator, usually measured under blocked force conditions.

Morphological computation: the capacity to provide a quick controlled response by using the adaptive dynamics and morphology of the muscles or soft actuators themselves when external perturbations occur in an uncontrolled environment.

Multi-element actuator: an actuator whose inherent stiffness and/or damping force capacity is on the order of its blocked (isometric) actuation force capacity.

Muscle synergy: the ability to activate specific groups of muscles synergistically to produce a particular movement, thereby reducing the dimensionality of muscle control and improving actuation timing, control, and efficiency.

Off-board energy: the energy located outside the actuator architecture that allows for long duration actuation or more actuation cycles than the onboard energy. For muscles, an example of this type of energy is oxygen supplied by the circulatory system for synthesis of ATP. For soft actuators, examples are external batteries (electro-activation) or pressurized tanks (fluid-driven).

Onboard energy: the energy integrated into the actuator's architecture that allows for short duration actuation or a limited number of actuation cycles. In biological muscle, this includes ATP, creatine phosphate, glycogen, and fat droplets stored within the muscle itself. In soft actuators, this level of energy integration is under development.

Performance: the level achieved by an actuator for a particular action that results from the actuator's properties, i.e. metrics.

Properties: the inherent or embedded attributes of the actuator.

Scalability: the ability of an actuator to work at multiple length scales due to series and parallel operation.

Soft actuator: an actuator whose physical form and flexible material allow for actuation (axial, radial, torsion, bending, and/or combinations of these) even under physical perturbations (bending, pinching, or pulling) when energy input is applied.

Specific average power: the average power developed by an actuator divided by its mass.

Specific peak power: the maximum peak power developed by an actuator divided by its mass.

Specific work: the work capacity of the actuator divided by its mass.

Stiffness: a quantity that represents resistance to deformation under load.

Total efficiency: the ratio of mechanical work output to chemical/electrical/etc energy input to the system (robotic/biological) hosting the actuator.

Tunable-element actuator: an actuator whose inherent stiffness and/or damping characteristics can be actively or passively adjusted.

Tunable compliance: the degree to which an actuator can change length (strain) in response to externally applied forces (stresses) when an energy input is applied. Tunable compliance is when compliance can be adjusted by an input signal, e.g. activation in the case of biological muscles.

Variable recruitment: the ability to selectively recruit motor units in series and parallel to grade the force generated by a muscle.

1. Introduction

For the past few decades, human-machine interactions (HMIs) [1–5] in applications such as smart exoskeletons and prosthetics [6, 7], wearables [8], intelligent surgical tools [9], and even humanoid robots [10, 11] have led scientists to study new soft actuation technologies that feature properties similar to biological muscles. These new soft actuators mimic the compliant nature of biological muscles and their use aims to overcome the drawbacks of conventional actuators in bio-inspired applications [12–14]. Conventional actuators, such as electric motors and hydraulic or pneumatic cylinder actuators, are widely used in robotics because they feature high accuracy, repeatability, reliability, high specific power, and efficiency [15–18]. However, their rigidity, weight, and lack of essential properties for adaptable muscle-like actuation make them unsuitable for many HMIs [19–21]. As a result, new bioinspired soft actuators are being developed and incorporated into various bioinspired robotic systems [22, 23]. These soft actuators can be fully synthetic [21, 24–29] or a hybrid between synthetic and biological materials, known as biohybrid or bio-syncretic robotics [30–33]. Among soft robotics, biohybrid robots constructed by the integration of living cells such as cardiomyocytes [34, 35], skeletal muscles [36, 37], and microorganisms [38–40] along with flexible materials can provide similar actuation to that one found in nature. Although biohybrid robotics is an attractive solution to mimic the actuation response of biological muscles, in this work, we intend to compare fully synthetic soft actuators with biological muscles because biohybrid robotic actuators can inherently mimic biological muscles properties due to their biological composition. For further information about biohybrid robotics, we direct the reader to recent publications that review several decades of this work [30–33].

A cursory study of fully synthetic soft actuators highlights a number of qualitative similarities to biological muscles, but quickly reveals deeper questions. What defines an 'artificial muscle' and more importantly, what properties of biological muscles distinguish them from engineered systems? This work compares both the performance and properties of soft engineered actuators to biological muscle in order to answer these questions.

Many recent reviews have provided updates on soft actuators [21, 24–29] and some of these compare performance of soft actuators with biological

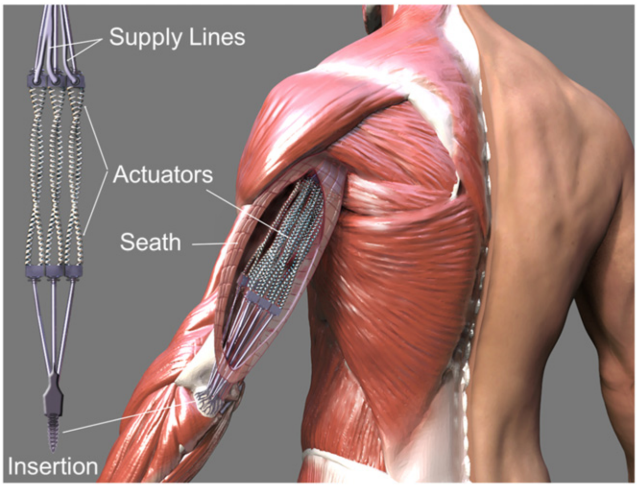

Figure 1. Integration concept of soft actuators (cavatappi artificial muscles) in a biological system (human body). Figure produced by Victor O Leshyk.

muscles. Our comparison focuses not only on performance criteria but also on investigating the unique properties of biological muscles and comparing these inherent properties with synthetic actuator technologies. In this work, we compare both worlds, soft and biological actuators, to better benchmark the new technologies and determine where advances are needed. In doing so, we refine the definitions of terms including artificial muscle and biomimetic actuator, which have at times been applied to soft actuators regardless of their similarities to their biological brethren. Additionally, understanding the unique properties of biological muscles that contribute to efficient and adaptive control of human movement [42, 43] may inspire new technologies capable not only of safe HMIs but also of seamless integration with humans (figure 1).

Traditionally, muscles have been viewed as motors (figure 2(a)) that convert activation input into a force output via a transfer function Act(t) [44]. The transfer functions typically range from 1st to 3rd order systems of differential equations [45–47]. While muscle models based on this principle perform reasonably well at predicting the force of isolated muscles in laboratory experiments [48], recent studies demonstrate that they perform poorly at predicting muscle force during natural movements of humans [49] and animals [46], especially at faster speeds [47] where the adaptive dynamic response of muscles is particularly important.

Recent models instead describe muscles as tunable active materials, similar to many soft actuators, that produce force when deformed by applied loads [41, 50, 51]. These models (figure 2(b)) emulate the adaptive dynamic response of muscles [52], based on activation-dependent changes in stiffness and equilibrium length of a spring [53]. The new models capture length-dependence of activation dynamics [54], and adapt automatically to changes in speed and terrain [50]. At the same time that biologists were evolving their view of muscles away from force generators to that of tunable active materials, engineers began exploring how synthetic actuation could be achieved through material deformation (soft actuation), an interesting convergence. A consequence is that the evolving view of muscles as tunable materials may provide inspiration for the design and control of soft actuators with a similar adaptive dynamic response that could provide versatility and safety of HMIs.

To compare soft actuators and muscles, we found it useful to define an 'actuation system volume' in order to better classify actuator features and delineate a system boundary for the scope of this work. In this volume (figure 3), energy flow and sensory feedback are included, as both are critical to the resulting system performance. We exclude consideration of features external to the actuator but necessary for operation, such as off-board energy storage (e.g. lipid reserves), external sensing (e.g. vision), and supervisory control (e.g. brain control). Other items within the actuator system boundary may not be present for many engineered systems. For example, onboard energy storage and embedded control are generally non-existent in synthetic actuators and are features to strive toward. Conversely, the energy required for homeostasis is an inherent cost of biological muscles that is not present in most synthetic actuators. This systemic view of the actuator includes features not often considered when comparing synthetic actuator designs, which often simply consider force generation capacity and occasionally, length and force sensing. Despite containing elements that may not be present in all actuation systems, the volume presented in figure 3 helps to classify features and thus provide a basis for comparison between disparate actuation modalities.

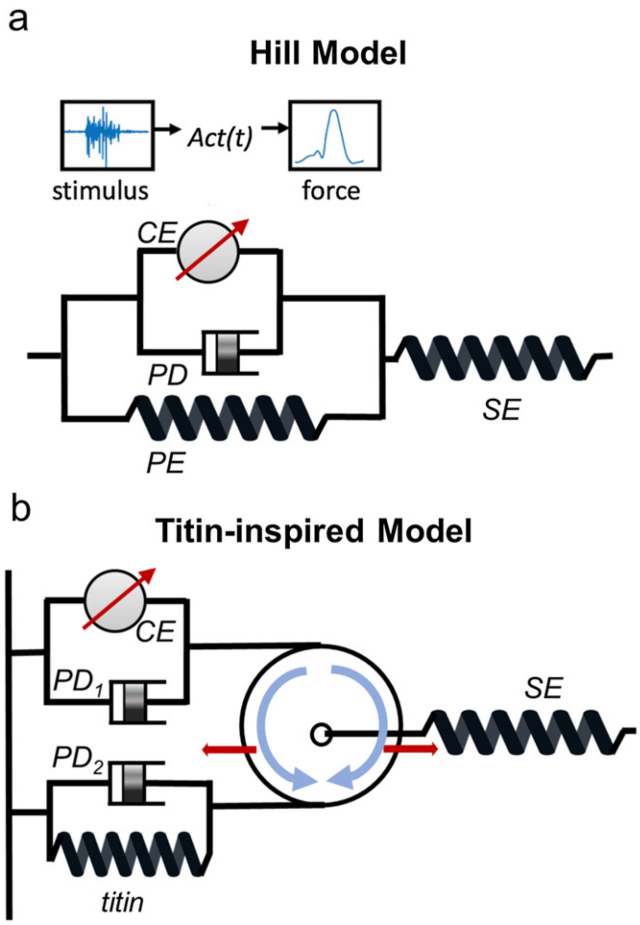

Figure 2. Muscle models. (a) Traditional model based on 'muscles-as-motors' has been in widespread use for decades. This model consists of a transfer function $Act(t)$ that converts an input stimulus into muscle force, plus modules that represent muscle properties including passive tension, force–length and force–velocity relationships. (b) Models based on 'muscles-as-tunable-materials' are a relatively new development. In these models, activation rotates a movable pulley in one direction, and the pulley rotates back in the other direction during deactivation (blue arrows) to simulate time- and length-dependent activation dynamics. The pulley translates along the long axis of a muscle when stretched or shortened by external or internal forces (red arrows). The length-dependent force is given by superposition of pulley rotation and translation. SE = series elastic element. PD = parallel damping element. PE = parallel elastic element. CE = contractile element. Reproduced with permission from [41].

Based on this definition of the actuation system volume (figure 3), we compare biological and engineered soft actuators. We begin by reviewing the latest muscle-like soft actuators in section 2, including the design, actuation mechanism, and some operational advantages and disadvantages. In section 3, we review the structure, actuation mechanism, models, and inherent properties that endow biological muscles with tunable compliance and adaptive dynamic response. This introduction to biological muscles also presents an engineering perspective of the muscle system as a tunable-element actuator [52, 55] to facilitate comparing the performance and properties of muscles and current soft actuators (section 4). Section 4 first compares performance metrics of conventional actuators, soft actuators, and biological muscles. Next, we compare those properties that provide biological muscles with tunable compliance and adaptability to the soft actuators presented in section 2. Finally, section 5 summarizes the current state of soft actuators in terms of performance and properties, and uses this comparative study to provide additional insight on soft robotic terms including biomimetic actuator, artificial muscle, and artificial supermuscle.

2. Soft actuation technology

The high accuracy and repeatability deployed by conventional, rigid electromechanical and fluidic actuators have been key for their widespread use in industry for the last century [56, 62]. However, their complexity and rigidity limit their deployment in areas such as biorobotics and compliant structures. This has led many scientists and engineers to search for new soft actuators that can adapt their dynamic response in a similar manner to actuation systems found in nature. The compliance of these new 'soft' actuators [12, 14, 27, 28] (ranging from ~0.1 to 10 MPa^{-1}) is similar to the passive compliance of biological muscles [63]. While new soft actuation technologies are continually being developed, we present a review of

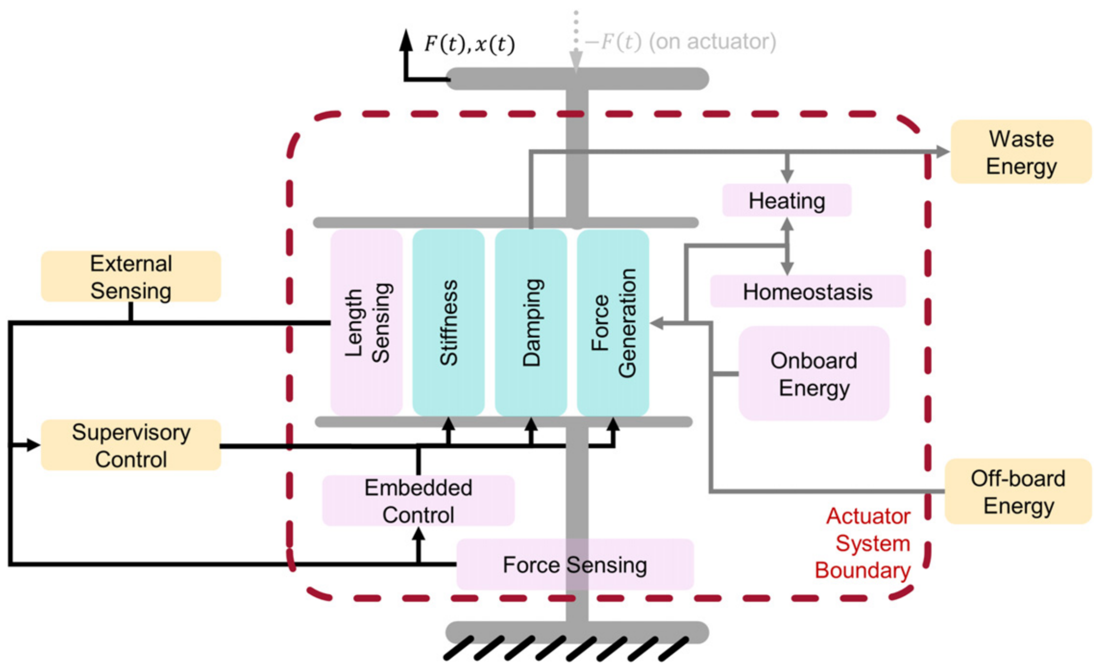

Figure 3. The control volume for the 'actuator system' is defined by the red dashed line boundary. Because internal elements are the focus of this work, this boundary was chosen to include only features and functions that occur within the actuator. Sensor and control mechanisms are shown with black arrows, while energy flow is shown with gray arrows. Biological and engineered actuators develop internal forces that, with inherent and tunable stiffness and damping, can affect the dynamic response of the system (adaptive dynamic response). Supervisory inputs affect both force generation and tuning. The integration of force and length sensing, embedded, control and onboard energy storage make biological muscles a highly integrated system. Some of this integration is available in engineered systems. All actuation systems require some external control and rate of energy transfer for operation. The external energy sources may be used for actuator work output or for maintaining environmental requirements for in-range operation (temperature, moisture, removal of waste products, etc). Inefficiencies and damping contribute to actuator heating and cooling (waste energy flow) requirements.

soft technologies that have significantly impacted this field and have similar performance to biological muscles. The soft actuators in this section are grouped using their actuation drivers, including electrostatic, thermal, and fluidic soft actuators. Finally, this section also briefly mentions other promising novel technologies for artificial muscles, including electrostatic bellow muscles (EBM), electro-ribbon actuators and electro-origami robots, water-responsive actuators (WRA), photo-responsive actuators (PRA), and eukaryotic DNA inspired artificial muscles.

2.1. Electrostatic actuators

2.1.1. Carbon nanotubes (CNTs)

Carbon nanotubes act as electrodes or counter electrodes, or both, when they are immersed in an electrolyte (figure 4). During actuation, electrostatic forces are generated by an asymmetric swelling or contraction of the CNT structure as a result of ion transport in the material matrix (figure 4(a)) [57]. CNTs can be fabricated from a single-walled sheet of graphite (single-walled nanotubes, SWNT) rolled into a cylinder with a diameter in the nanometer scale (figure 4(b)-left). They can also be found in a nested configuration with more than one layer (multi-walled nanotubes, MWNT, figure 4(b)-right) or a hybrid configuration with other materials such as nylon fibers (figure 4(c)). Despite the different configurations, they all share the same actuation mechanism. CNT actuators are composed of many nanotubes in the form of films and yarns. The porosity of this material enables fast ion transport which translates into fast actuation, strain rates, and specific power [64]. However, the mechanical properties that make CNTs strong and stiff (tensile modulus of 1 TPa and tensile strength from 20–40 GPa [25, 65, 66]) do not allow for high deformations, leading to a limitation in their strain [25]. Although strains are increased in twisted and coiled CNT actuators (figures 4(d) and (e)), similar to the twisted polymer actuators discussed in section 2.2.1, their actuation response time also increases, making them much slower than biological muscles [60, 67]. In this work, we focus on single fiber CNTs as they have been most studied and utilized in applications [25, 68]. Single fibers have been combined to form smart textiles, which have been used to assist individuals with limited mobility [59]. Finally, it is important to mention that extraction of carbon nanotube fibers is currently difficult, and the fabrication process makes these actuators expensive [69].

2.1.2. Electro-active polymers (EAPs)

Electroactive polymers are capable of developing high mechanical strain in response to electrical stimuli [73]. EAP materials exhibit some beneficial features

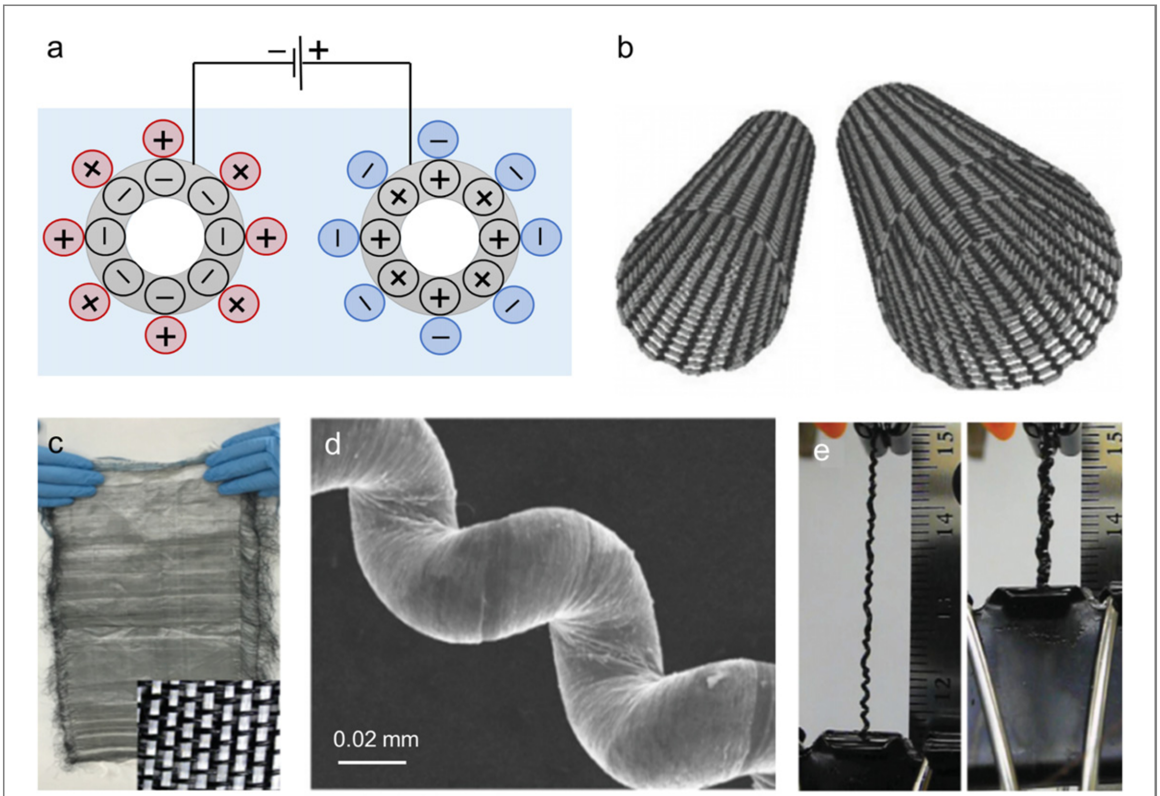

Figure 4. Carbon nanotube actuators (CNTs). (a) Schematic illustration of charge injection in a nanotube-based electromechanical actuator. An applied potential injects charge of opposite sign in the two pictured nanotube electrodes, which are in a liquid or solid electrolyte (light blue background). The different charges in each electrode are balanced by ions from the electrolyte (denoted by the charged spheres on each nanotube cylinder). Each illustrated single nanotube electrode represents an arbitrary number of nanotubes in each electrode that act mechanically and electrically in parallel. Depending on the potential and the relative number of nanotubes in each electrode, the opposite electrodes can provide either in-phase or out-of-phase mechanical deformations. From [57]. Reprinted with permission from AAAS.(b) Left: single-walled nanotube, SWNT. Right: multi-walled nanotube, MWNT. From [58]. Reproduced with permission from Dove Medical Press. (c) Fabric knitted using nylon fibers as weft and CNT fibers as warp. The inset shows the pattern details of the fabric. [59] John Wiley & Sons.(d) Chemically actuated thin coiled silicone-CNT hybrid yarn. (e) A 500 μm thick coiled yarn contracts by 50% under 2 MPa tensile stress when exposed to hexane. The tensile stress is with respect to the non-coiled diameter of hybrid yarn before solvent absorption. [60] John Wiley & Sons.

for biomimetic implementations such as high strain and power density, versatility, and scalability [74]. EAPs are normally designed in a sandwich configuration with a soft insulating elastomer membrane between two compliant electrodes. Actuation is driven by an electric field generated by the voltage applied between the electrodes. While there are many different types of EAPs, here, we focus on dielectric elastomer actuators (DEAs) because these display the best performance in terms of linear actuation [75, 76]. DEAs can generate high deformations as a result of electrostatic interactions between the electrodes. The actuation mechanism in DEAs is based on the principle of capacitors. When an external voltage is applied, opposite charges attract in the electric field direction and repel in the perpendicular direction. The generated Maxwell stress creates compressive forces on the dielectric material (polyurethanes, silicones, or acrylics) along the direction of the applied voltage, leading to an expansion of the dielectric material in the other two directions (see figure 5(a)). The elastomers of DEAs are usually silicone or acrylic materials which achieve large deformation due to their low elastic modulus (1 to 10 MPa). Additionally, they also have a fast actuation response, making them suitable candidates for bioinspired applications. Walking robots like MERbot and FLEX 2 (figures 5(c) and (d)) have been actuated using DEAs in a roll configuration (figure 5(b)) [55, 74, 75, 77, 78–80]. However, the high voltages required for actuation can create challenges for practical implementation of their power electronics.

2.1.3. Hydraulically amplified self-healing electrostatic actuators (HASELs)

Hydraulically amplified self-healing electrostatic actuators are electrohydraulic activated muscle-mimetic actuators fabricated from an elastomeric shell partially covered by a pair of opposing electrodes and filled with a dielectric liquid. The use of hydraulic principles in HASEL actuators results in the capability to scale actuation force and strain; features also used in other device classes such as microhydraulic systems [81] and hydrostatically coupled DE actuators [82]. Upon voltage application, the induced electric field generates an electrostatic Maxwell stress that pressurizes and displaces the

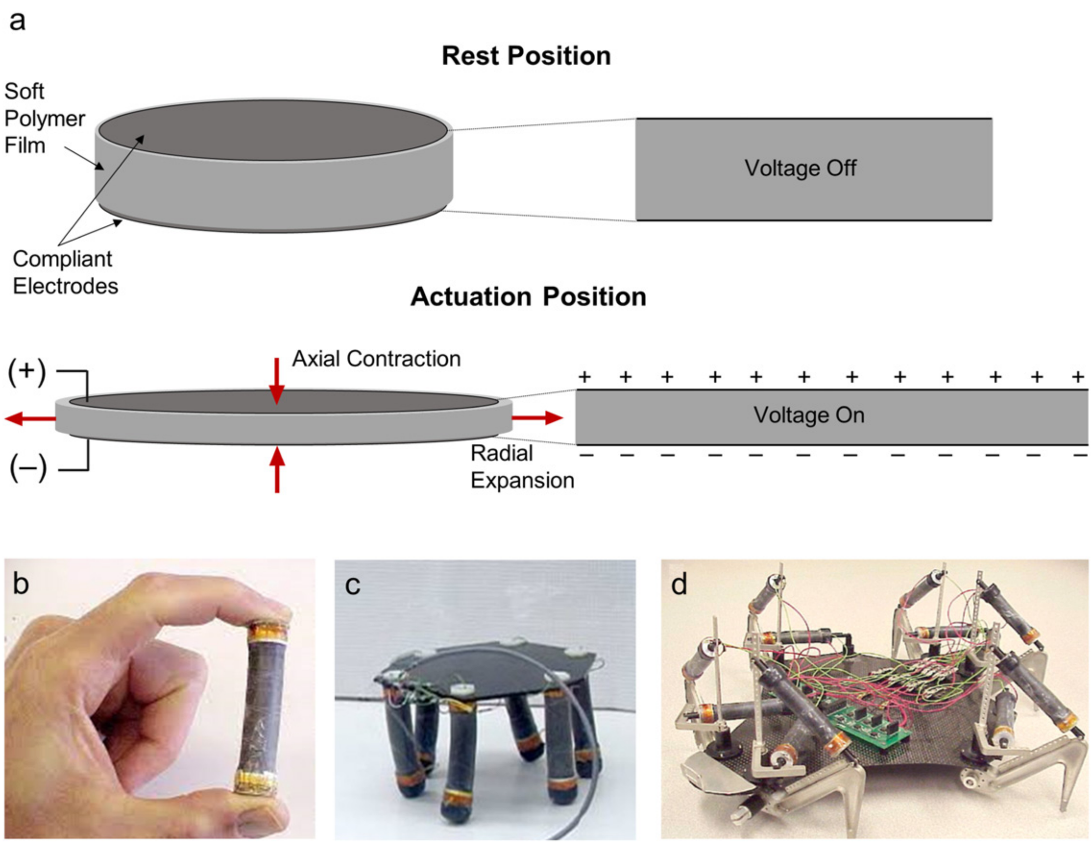

Figure 5. Electro-active polymers (EAPs). (a) Operating principle of dielectric elastomer actuators (DEAs). When a bias voltage is applied across an elastomer (soft polymer) film coated on both sides with compliant electrodes, Coulombic forces compress the film in the axial direction and expand it radially. [61] John Wiley & Sons. (b) One degree of freedom multifunctional electroelastomer roll (MER) actuator fabricated with two prestrained films rolled around a compressed central spring (the spring is located at the center of the roll and covered by the films). (c) MERbot, a robot using a 2-DOF MER for each of its six legs. Reproduced with permission from [74]. (d) FLEX 2 robot using MER actuators from (b). Reproduced with permission from [77].

liquid dielectric, leading to contraction (figure 6(a)). HASELs have been developed in different configurations: Planar-HASELs (figure 6(c)), Peano-HASELs (figure 6(b)), Donut-HASELs and bio-inspired designs such as a scorpion tail that can contract, curl, and twist [70, 71, 83]. However, their actuation relies on the same mechanism in which a pouch is designed and fabricated to develop the desired actuation response under internal pressurization created by the generated Maxwell stresses. In this work we mainly focus on Planar- and Peano-HASELs as their contraction actuation is similar to biological muscles in almost all their metrics (table 1) [70, 71]. In addition, HASELs also have an inherent strain sensing property; measured capacitance is low when the actuator is fully flexed and high when fully extended. This self-sensing capacity of HASELs can be a useful feature for control, similar to the mechanical impedance of biological muscle [84, 85]. Unlike traditional solid DEAs, which would be permanently damaged due to a high electric field, the use of a liquid dielectric enables HASEL actuators to self-heal from a dielectric breakdown. The self-healing property improves the durability and stability of HASELs. Finally, it is important to mention that HASELs require high voltage (>5 kV) for activation, which could lead to the risk of electroshock of users. Although high voltage requirements usually translate into voluminous power electronics [70, 71], new research has shown HASEL applications with portable electronics and batteries (3.7 V, 500 mAh lithium polymer battery with a 5 V power booster); however, the duration and efficiency of such set-ups has not been reported [83].

2.2. Thermal actuators

2.2.1. Twisted polymer actuators (TPAs)

Twisted coiled polymer actuators are thermally driven linear actuators with a specific work and power 64 and 84 times that of biological muscles [90, 178]. The actuation response of TPAs results from the anisotropic thermal properties of the untwisted precursor material (figures 7(a) and (d)), which experiences axial thermal contraction and radial thermal expansion (similar to the asymmetric response of carbon nanotubes to ion transport). The thermal anisotropy of the precursor monofilament translates into shear strain on the twisted elemental unit (figure 7(b)) and, in turn, axial contraction on the coil-shaped TPA upon heating (figures 7(c) and (e)). These actuators are fabricated by twisting a drawn

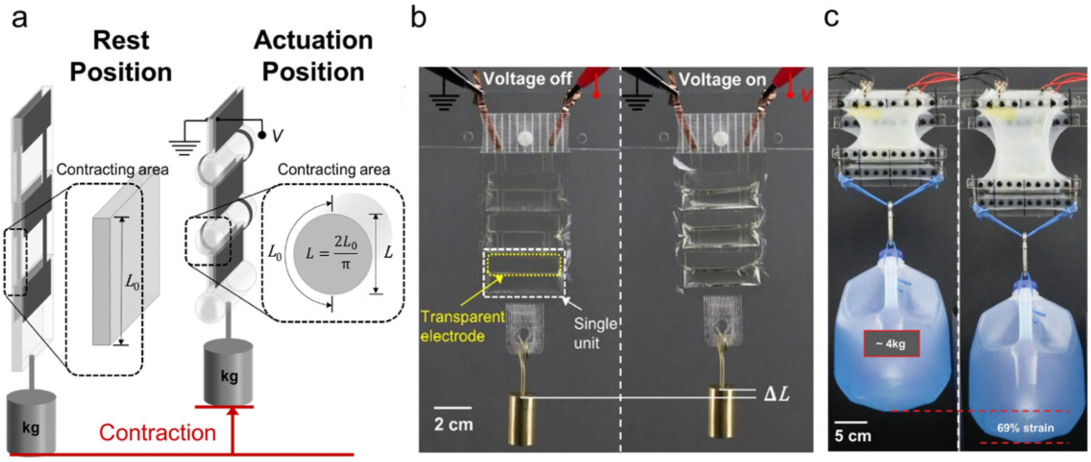

Figure 6. Hydraulically amplified self-healing electrostatic actuators (HASELs). (a) Actuation mechanism of Peano-HASEL actuators. Each unit consists of a flexible rectangular pouch filled with liquid dielectric. Electrodes are placed over a portion of the pouch on either side. When the voltage (V) increases, electrostatic forces displace the liquid dielectric, causing the electrodes to progressively close. This forces fluid into the uncovered portion of the pouch, causing a transition from a flat cross section to a more circular one, which leads to a contractile force. (b) Three-unit Peano-HASEL actuator shown lifting 20 g on application of 8 kV across the electrodes. From [70]. Reprinted with permission from AAAS. (c) Contractile linear actuation of six Planar-HASEL actuators lifting a gallon of water. From [71]. Reprinted with permission from AAAS.

polymer monofilament until the monofilament buckles in twist and coils, or by wrapping the twisted monofilament around a mandrel to create a coil. TPAs are spring-shaped (figure 7(e)), and can be assembled in groups to form braided structures (figures 7(f) and (g)) [178]. TPAs are inexpensive, often fabricated from fishing line or sewing thread, and have been deployed in robotics (figure 7(h)) [72, 90, 91], medical devices [90], and active textiles [92]. Although TPAs outperform skeletal muscles in many metrics, including specific work/power and maximum stress/strain (see table 1), thermal activation is generally inefficient and slow. Additionally, most of the drawn polymers used in TPA fabrication are highly viscoelastic [93, 94] and hygroscopic, which causes their actuation response and performance to depend on moisture content of the material [95]. Moreover, the temperature changes required for actuation affect the viscoelasticity and hygroscopic properties of TPAs, which leads to modeling challenges, and therefore, a lack of accurate control algorithms [94, 96–98,182].

2.3. Fluidic actuators

2.3.1. Pleated pneumatic artificial muscles (PPAMs)

Among fluid-based muscle-like actuators, pleated pneumatic artificial muscles—an recent version of McKibben actuators—develop contractile actuation by inflating an unstretchable membrane surrounded by numerous pleats in the axial direction [100]. In all McKibbens (regular and thin), the macroscopic anisotropy causes the device to contract in length and expand radially when pneumatically loaded [101, 102]. Upon inflation, the pleated membrane unfolds without straining the material, producing radial growth and axial contraction of the actuator (figures 8(a) and (b)). PPAMs have the highest performance metrics, which makes them potential candidates for HMIs (figure 8(d)) [103, 104] and other bioinspired applications (figures 8(c) and (e)) [87, 89]. The pleated configuration of McKibbens was developed to eliminate their multi-component nature that causes frictional losses and hysteresis, which also limited their controllability [101, 105]. PPAMs can outperform many metrics such as specific work, average specific power, and actuation stress compared to biological muscles [86, 100]. To maintain low mass, PPAMs typically deploy air as the working fluid for actuation. Due to gas compressibility, low pumping efficiency, and the relatively large amount of fluid required for operation, they generally achieve low total efficiency [106–108]. It is also important to note that the substantial radial growth resulting from inflation limits the parallel operation of PPAMs, making them useful only in volumetrically inefficient configurations. This limitation prevents variable recruitment in bioinspired applications.

2.3.2. Flexible elastomeric actuators (FEAs)

Flexible elastomeric actuators are fluid-driven continuum solid structures pre-designed and programmed to mimic the motion found in some biological systems such as octopuses (figure 9(c)) or starfish (figure 9(b)). Their working principle is inspired by the Venus flytrap, whose flexible membranes are pressurized with fluid leading to a quick trap closure (100 ms) [109]. FEAs are usually programmed to develop bending as their actuation response, but other deformations such as elongation, contraction, and torsion are also possible; however, in this work we focus on bending and contractile FEAs (figure 9(a)). Different subgroups of FEAs include soft pneumatic

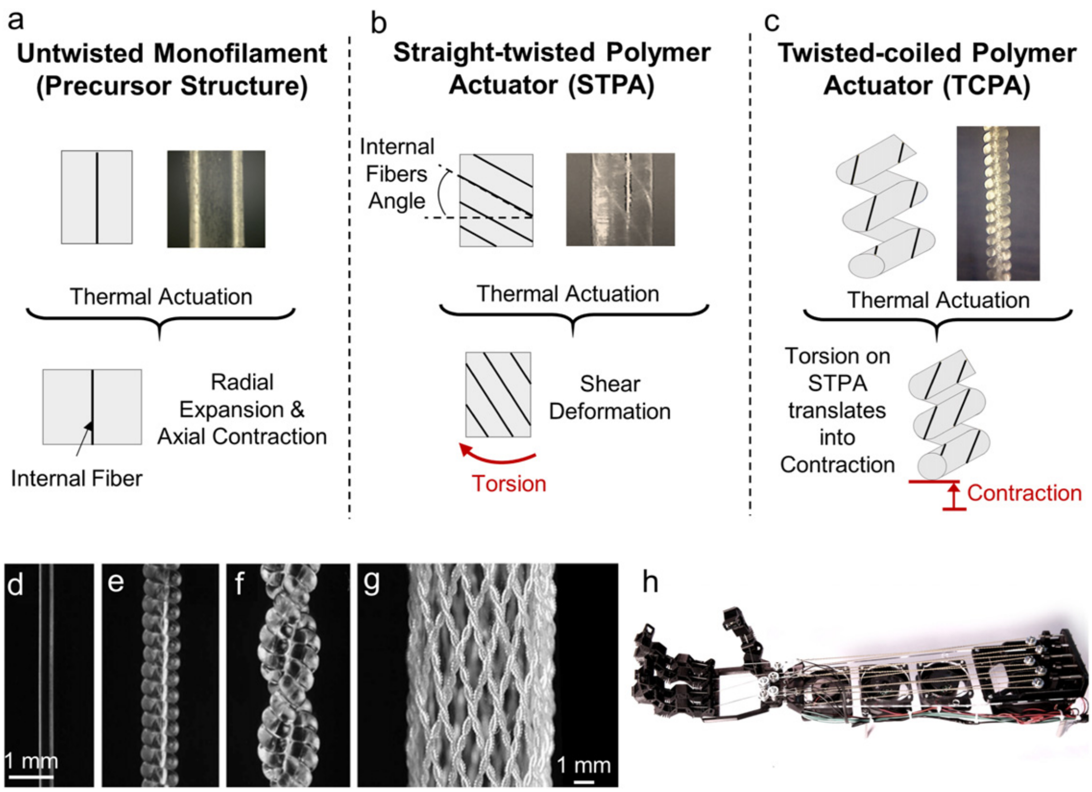

Figure 7. Twisted polymer actuators (TPAs). Actuation response under thermal loading of (a) an untwisted straight monofilament (precursor structure), (b) straight twisted polymer actuator (torsional actuator), and (c) twisted and coiled polymer actuator (axial actuator). Optical images of: (d) a non-twisted 0.3 mm diameter monofilament, (e) a TPA after coiling by twist insertion a 0.3 mm diameter monofilament, (f) a two-ply muscle formed, (g) a braid formed from 32 two-ply, coiled, 102 μm diameter fibers. From [178]. Reprinted with permission from AAAS. (h) A robot hand constructed using TPAs to execute various grasping maneuvers using open loop control. © [2015] IEEE. Reprinted, with permission, from [72].

actuators (SPAs) [183] and flexible-fluidic actuators (FFAs) [110], but they all rely on the same actuation principle. They are normally fabricated using 3D printing and modeling techniques, making them easy to fabricate and affordable. In their fabrication, arrangements of extensible and inextensible regions are conveniently designed to create specific bending, torsion, elongation, and contraction that translates into motion when fluid pressure is applied, which allows control of their topology. Their materials and design are the source for their actuation properties (mechanical compliance, topology and geometry, maximum stress and strain, efficiency, etc), which means they can be designed to perform specific tasks (single-tasking) such as walking, grasping, pulling, or twisting. FEAs can change their compliance as a function of internal pressure [183], generating high strains and block forces [27]. However, as is also true for all polymer-based soft actuators, some of these metrics can be affected by environmental conditions such as temperature and humidity, as the mechanical properties of the precursor materials depend on such [27], which can hinder control. The mechanical properties of these materials and their arrangements lead to non-linearities during actuation which are enhanced during pneumatic activation due to compressibility [111]. Although liquid-based devices can exhibit more linear behavior than those driven pneumatically [112], creating closed-form models for these actuators is still an arduous task, and finite element methods are usually applied when predicting their actuation response [113], limiting their broad adoption. The applications include medical devices, bio-inspired applications, or HMIs where inherent compliance and adjustable stiffness are needed [99, 110, 114, 183].

2.3.3. Fluid-driven origami-inspired artificial muscles (FOAMs)

Fluid-driven origami-inspired artificial muscles are origami-based vacuum-driven actuators consisting of a repeated zigzag-pattern skeleton within a sealed bag. When negative pressure is applied to the actuator, the air inside the bag exits and the zigzag pattern leads to contraction (figure 10(a)). The internal skeleton found in FOAMs can be designed to develop many different actuation responses in addition to the single-degree-of-freedom contractile motion shown in figure 10(c). FOAMs have been fabricated at small scales (figure 10(b)), shown to perform under water, designed to dissolve when in contact with hot water, and onboard energy and sensors have been integrated into their skeletons [181]. These actuators develop high strains, specific work and average power,

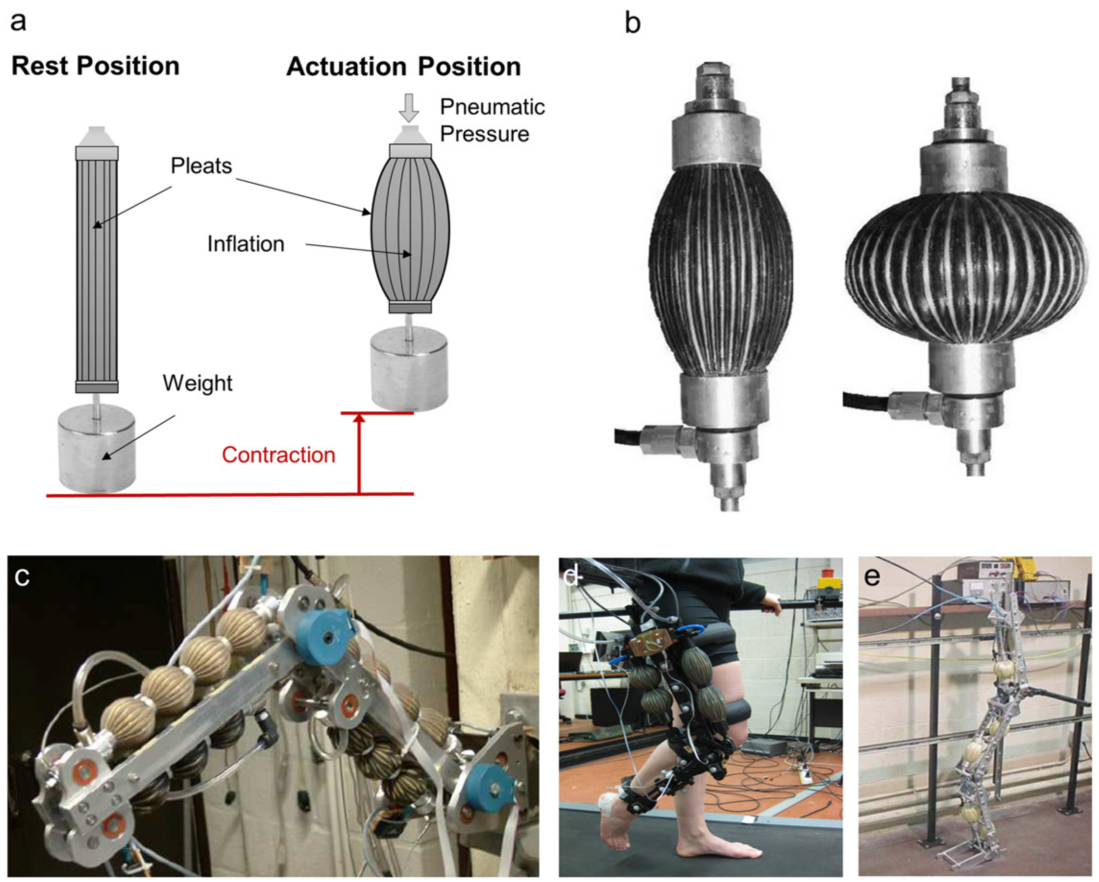

Figure 8. Pleated Pneumatic artificial muscles (PPAMs). (a) Schematic illustration of the actuation response of a PPAM when inflated. (b) PPAM shown at two different actuation stages: at rest (left) and at maximum contraction (right). [86] 2012, reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com). (c) Robotic manipulator actuated by serially arranged PPAMs. Reproduced with permission from [87]. (d) KNEXO, a knee exoskeleton prototype powered by PPAMs. [88] 2011, reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com). (e) Right half of the 'lucy leg' attached to a sliding mechanism. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Autonomous Robots[89] The pneumatic biped "lucy" actuated with pleated pneumatic artificial muscles", Verrelst, B., Ham, R. V., Vanderborght, B., Daerden, F., Lefeber, D., and Vermeulen, J., (c) 2005.

and have high fluidic-to-contractile energy conversion efficiencies. Although they have been shown to perform well in portable applications using small vacuum pumps, their negative pressure rate source is usually low, which leads to a slow response. Furthermore, the large strains generated by FOAMs significantly decrease with small load increments, similar to the muscle-length force dependence found in biological muscles [181]. Finally, as is true for all vacuum-driven actuators, there is a theoretical limit to the stress generated in these devices based on the difference between the pump's vacuum capacity and the local atmospheric pressure. Positive pressure actuators do not suffer from such a limit.

2.3.4. Origami-based vacuum pneumatic artificial muscles (OV-PAMs)

Similar to FOAMs, origami-based vacuum pneumatic artificial muscles consist of a sealed chamber made from polyvinyl chloride connecting a top and a bottom plate with evenly spaced transverse reinforcements (figures 11(a) and (b)), rather than using an internal foldable skeleton like FOAMs. Negative pressure inside the chamber causes the PVC film to fold and the transverse reinforcements to stack up, leading to contraction. OV-PAMs have excellent efficiency close to one. However, their specific power and maximum strain are approximately ten times less than those of biological muscles [115, 116]. OV-PAMs can maintain a strain close to 100% while generating their maximum force, which allows these actuators to generate force independently of their length, unlike FOAMs and biological muscles. Similar to FOAMs, OV-PAMs are also vacuum activated, and their actuation response is usually slow when using portable vacuum pumps (figure 10(c)), resulting in low specific power. Additionally, OV-PAMs are voluminous, and their narrow degree of flexibility could limit their implementation in small and flexible robotic applications [115, 116].

2.3.5. Cavatappi artificial muscles

Cavatappi artificial muscles use a similar actuation mechanism as twisted polymer actuators (TPAs), but bypass the inefficient thermal actuation driver. These devices use anisotropic mechanical properties

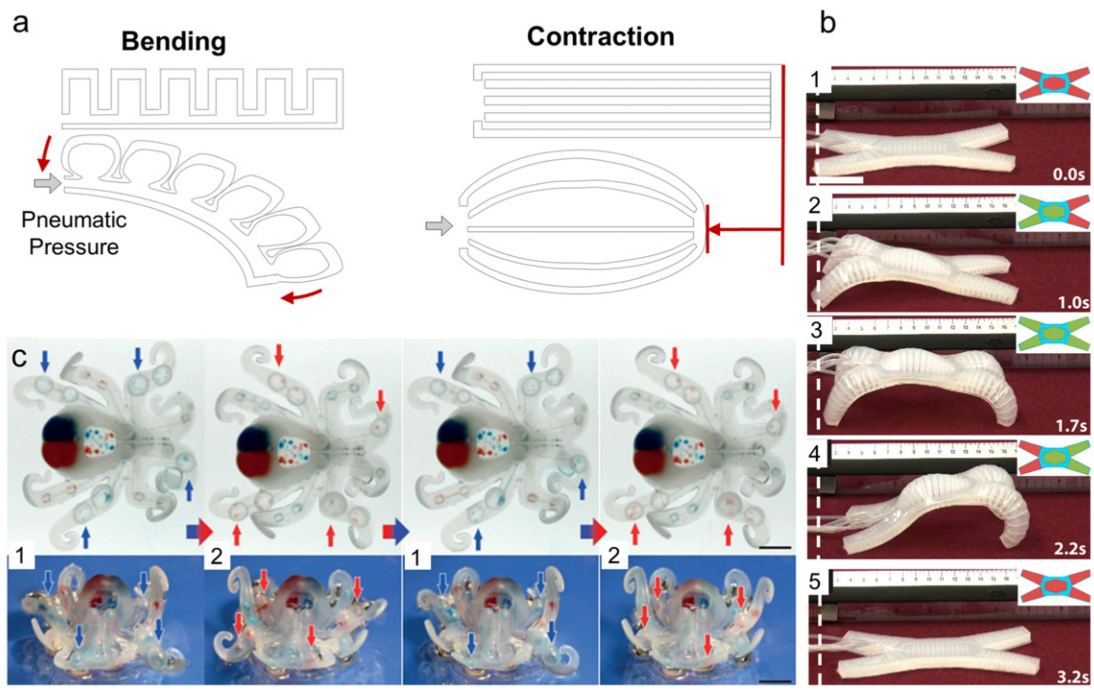

Figure 9. Flexible elastomeric actuators (FEAs). (a) FEA designs and actuation principles: bending actuator (top-left), contractile actuator (top-right). All FEAs actuate upon inflation as a result of their design and flexible materials. (b) Walking cycle of a multigait soft robot inspired by animals (e.g., squid, starfish, worms). This soft robot uses the pressurization of the legs' internal membranes to create an undulation deformation that translates into a walking motion of the entire structure. A particular leg's pressurization is shown (insets) in green, and inactive legs are shown (insets) in red. Scale bar, 4 cm. Reproduced from [183]. CC BY 4.0. (c) Operation of an octobot autonomously alternating between actuation states (two actuation cycles). During actuation, alternating groups of tentacles are actuated separately, blue ('1') and red ('2'). When the inflatable chambers in the tentacles are internally pressurized with fluid, the tentacles rise and when pressure is released, they lay down. Scale bars, 10 mm. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature[99] An integrated design and fabrication strategy for entirely soft, autonomous robots, Wehner, M., Truby, R. L., Fitzgerald, D. J., Mosadegh, B., Whitesides, G. M., Lewis, J. A., and Wood, R. J., (c) 2016.

of drawn polymer tubes to develop contraction but employ internal pressurization rather than temperature changes for actuation. These tubes can be configured as torsional actuators when twisted or as linear actuators when helically coiled with similar shape to cavatappi pasta (figures 12(c) and (d)). After drawing (figure 12(a)) and twisting (figure 12(b)), hydraulic or pneumatic pressure applied inside the tube results in localized untwisting of the helical microstructure. This untwisting manifests as a contraction of the helical pitch for the coiled configuration (figure 12(c)). As a result of their hydraulic or pneumatic activation and the more constant material temperature, these devices outperform TPAs in terms of actuation bandwidth, efficiency, and practical implementation. Cavatappi can exhibit contractions 50% of their initial length, mechanical contractile efficiencies near 45%, and specific work and power metrics ten and five times higher than biological muscles, respectively [117]. Small-scale cavatappi have also been designed with an outer diameter of less than 1 mm. Activation by internal pressurization allows configuration in parallel, and scalability similar to biological muscle fibers without the need to isolate individual actuators to avoid interference by the activation energy source (uncontrolled heat transfer in TPAs). In principle, these parallel configurations (figures 12(e) and (f)) could perform variable recruitment and muscle synergy, and be used in bio-inspired muscle-like applications. Despite the minimal amount of fluid required for actuation (low flow rates), one drawback of cavatappi is the high pressure needed for actuation ($\sim$1.5 MPa). Although small high-pressure pumps are available, they are expensive and reduce the economy of cavatappi in many applications.

2.4. Other promising soft actuation technologies

In addition to those actuators described in the previous sections, there are several other technologies whose actuation principles and designs might provide useful insights to achieve successful muscles substitutes. Although the actuators described in this section are promising in the field of artificial muscles, they still do not meet most of the performance metrics of biological muscles or they have not been investigated yet in depth.

Along with DEAs and HASELs, other electrostatic actuators have been reported in the past years. Electrostatic bellow muscles (EBMs) have used the previously mentioned electrostatic actuation principles along with thin films, liquid dielectrics, and rigid polymeric stiffening elements to form a circular shaped actuator capable of out-of-shape contraction [118]. These actuators are simple-to-make and

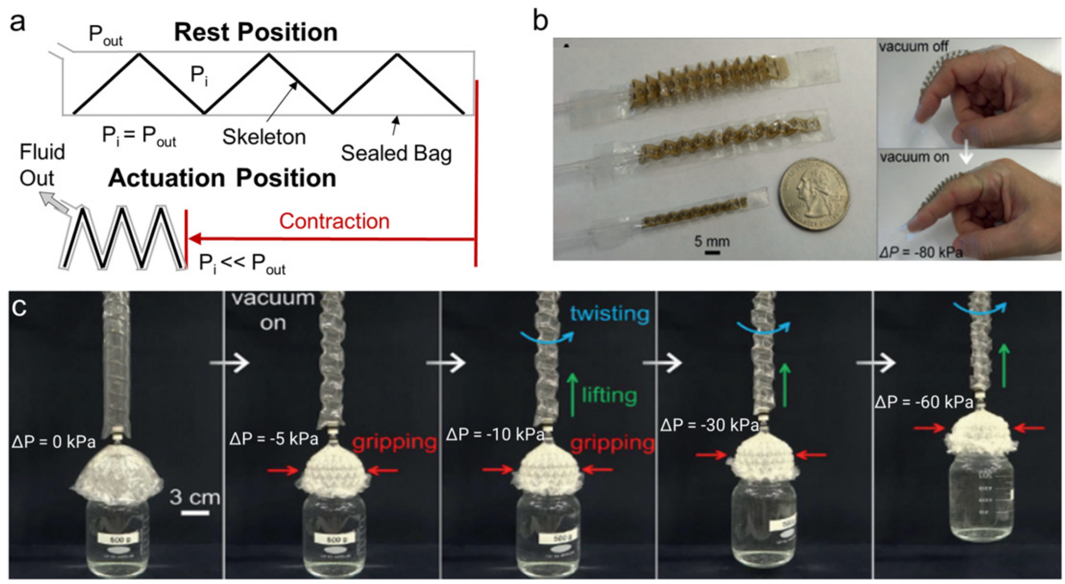

Figure 10. Fluid-driven origami-inspired artificial muscles (FOAMs). (a) Actuation mechanism. Upon application of negative pressure ($P_{in} \ll P_{out}$), the zigzag-pattern skeleton folds as a result of air exiting from the sealed bag. (b) Miniature linear actuators use polyethyl ether ketone (PEEK) zigzag origami structures as skeletons and PVC films as skins. (c) A bottle of water is gripped, lifted, and twisted by a single-channel vacuum-driven robotic arm. Reproduced from [181]. CC BY 4.0.

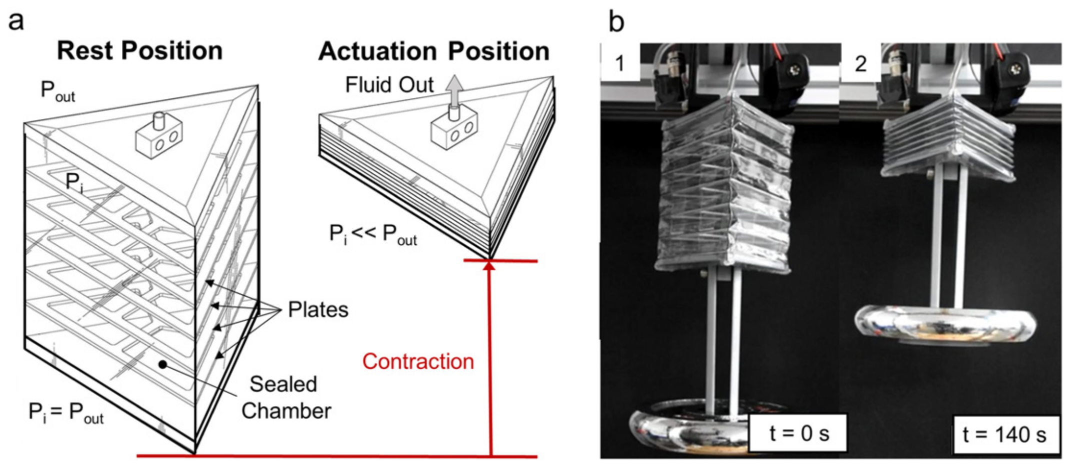

Figure 11. Origami-based vacuum pneumatic artificial muscles (OV-PAMs). (a) Actuation mechanism. Upon applied negative pressure, the air inside the actuator chamber exits and the actuator contracts. (b) Folding of the corners of the actuator. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, International Journal of Precision Engineering and Manufacturing-Green Technology te the potential elastic energy storage capacity of cavatappi [116] Efficiency of origami-based vacuum pneumatic artificial muscle for off-grid operation, Lee, J.-G., and Rodrigue, H., (c) 2019.

low-cost and can deploy fast actuation strain (actuation contractions and strain rates greater than 40% and 1200%/s, respectively) and efficiency similar to biological muscles. Furthermore, they can also work as harvesting systems during inactive actuation phases which can be used to increase the energy efficiency of the actuator. However, at the EBMs current state, some of their key metrics are orders of magnitudes lower than those found in biological muscles. These metrics are specific work (0.0012 kJ kg^{-1}), specific power (0.015 kW kg^{-1}), and maximum actuation stress (0.004–0.006 MPa) [118]. Electro-ribbon actuators and electro-origami robots use an origami fold whose opposing sides are oppositely charged. At the fold hinge, an electric field is developed exerting an electrostatic force. Such electrostatic force is amplified by using a small bead of high permittivity and breakdown strength liquid dielectric, which in turn, enable useful work while the hinge closes [119]. Multiple actuator configurations are possible using this actuation mechanism; however, the performance metrics of these actuators strongly depend on the actuator design. For example, the designs for high specific energy (0.007 kJ kg^{-1}) and high peak specific power (0.1 kW kg^{-1}) are different. Thus, while a specific electro-ribbon actuator might achieve high performance in one of these metrics, there is not a generic or

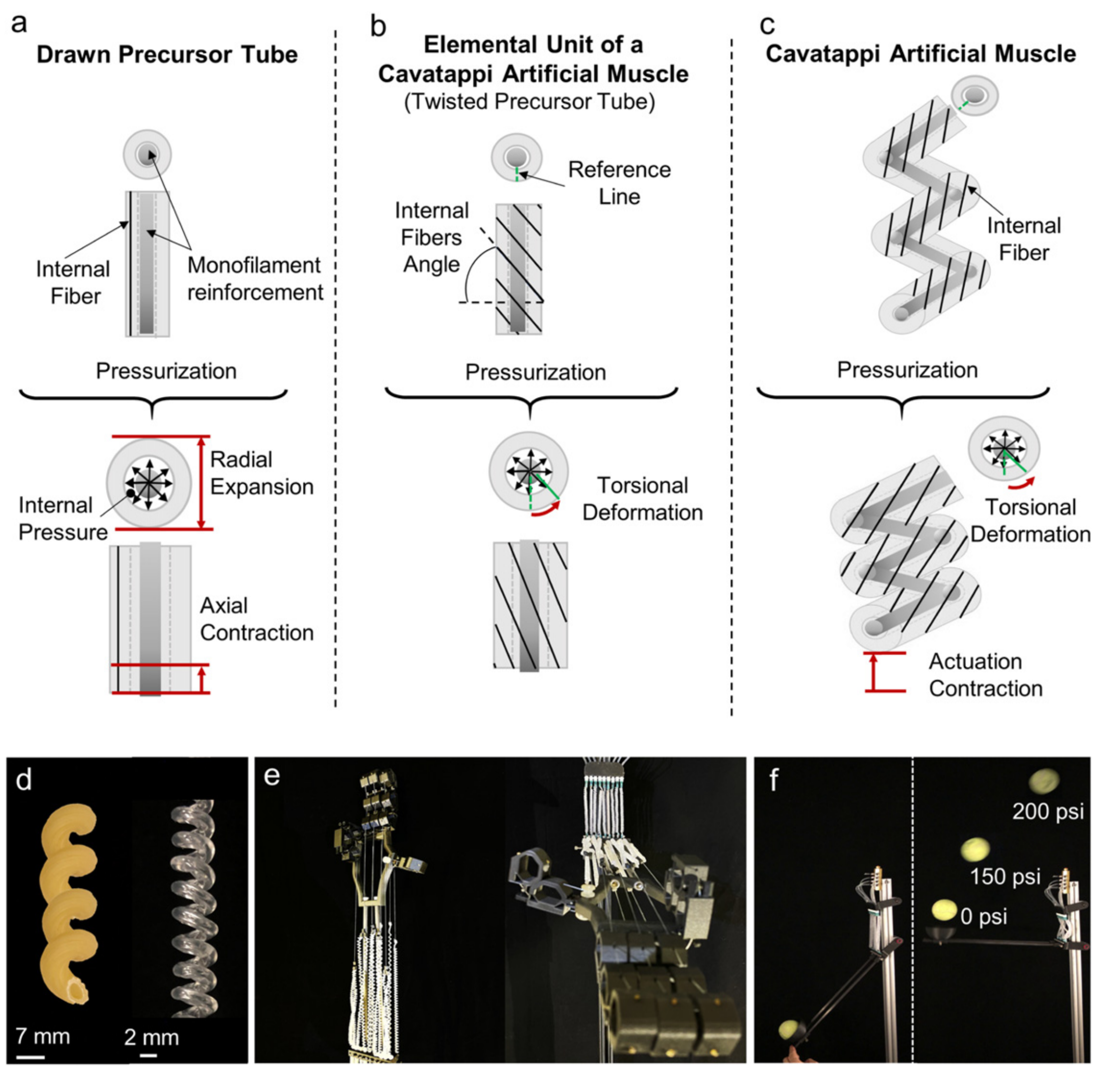

Figure 12. Cavatappi artificial muscles. Actuation response of cavatappi artificial muscles. (a) Internal pressurization produces axial contraction and radial expansion in the drawn precursor tube, (b) untwist in the cavatappi elemental unit, and (c) linear contraction in the cavatappi artificial muscle (coiled structure). (d) The helical pasta-like shape of cavatappi gives inspiration to the actuator's name, and a cavatappi artificial muscle (right) made from a 1.8 mm OD/0.85 mm ID drawn tube, which has been pre-stretched and annealed after fabrication in order to increase the helix pitch. (e) Robotic hand and arm system with cavatappi artificial muscles in place. (f) Cavatappi used to catapult a ball to demonstrate the potential elastic energy storage capacity of cavatappi. From [117]. Reprinted with permission from AAAS.

standard actuator that can meet all the performance metrics of biological muscles [119].

Others have focused their effort on soft actuators that generate mechanical motion in response to changes in the moisture content in their natural or synthetic material structure, the driver being usually the external relative humidity (RH) [120]. These soft actuators are called water-responsive (WR) actuators and have been found to be great candidates for energy-related applications. Some of these applications are weather-responsive architectural systems that can autonomously adjust their openings upon changes in local RH [121, 122] or smart textiles that open and close in response to human body's sweating to facilitate comfort [123–125]. The same actuation mechanism has been deployed in actuation systems. Overall, these actuators can perform similar actuation performance metrics as biological muscles; however, most of these actuation technologies require of long times to generate an actuation cycle [124, 126–128]. Additionally, environmental RH is a driver difficult to control, which makes these actuators face multiple challenges in some bioinspired applications.

Photoresponsive materials have also been used to generate actuation [129]. In this soft actuation subfield, photochemical transformation and photothermal heat generation are the most exploited actuation mechanisms. Although these have been shown to be promising in fields like micro-robotics [130], similar limitations as the ones found for WR actuators are presented when they are deployed as artificial muscles. Their timescale of deformation typically on the order of seconds or longer due to light propagation, interplay between isomerization kinetics, and mechanical properties of the matrix [129]. Furthermore, photoactuation on smaller length scales for the miniaturization of photomechanical devices remains a challenge as a result of limitations in light delivery in such scale [129].

Finally, the thousandfold contraction mechanism of eukaryotic DNA into the cell nucleus was used to create artificial muscles under the name's work: dual high-stroke and high-work capacity artificial muscles inspired by DNA supercoiling [131]. These soft fiber actuators could generate contractions close to 90% and maximum specific works 36 times higher than biological muscles when immersing the actuators in base and acid solutions [131]. However, and similar to WR and photoresponsive soft actuators, their actuation response is slow and their driver is difficult to use in some bio-inspired applications.

In conclusion, the above soft actuation technologies have not been extensively reviewed in this work because there are still challenges present to meet some of the key metrics of biological muscles as such technologies are found in their early stages. However, the aforementioned soft actuators might help to inspired future soft actuation technologies.

3. Biological muscles

Animal and human muscles and the bodies that contain them integrate multiple components, such as power source (ATP), actuators, strain and force sensors [84, 85], and control circuits in the spinal cord and brain, into a relatively compact material architecture [42]. The unique structure of biological muscles provides these actuators with several properties that are usually limited in conventional actuators. Therefore, compared to robots, animals exhibit remarkably agile, versatile, adaptable and efficient movements [132]. In terms of versatility, any muscle can function as a motor, brake, strut or spring depending on the activation and strain that it experiences during movement. In terms of adaptability, muscles instantaneously adjust their material properties in response to unexpected perturbations [43], becoming less stiff and more damped when stepping into a hole [133], and more stiff when encountering an obstacle in the path of movement [134]. This section presents a top-down, multi-scale introduction to biological muscle structure and function, actuation mechanism, control, and key properties that make muscles unique and would be useful to incorporate in soft actuators.

3.1. Structure and function

Skeletal muscles of vertebrate animals and humans are connected to bones by collagen fibers that form tendons or aponeuroses (figure 13(a)). When a muscle is activated, its force is transmitted through the tendons to the bones to produce a torque about a joint. When this torque overcomes opposing loads (antagonistic muscles and external loads), actuation is achieved by changing the distance between the anchor points. Although nerves, blood, and lymphatic vessels are woven throughout, muscles mainly consist of bundles of fibers, 5–100 μm in diameter, connected in parallel (figure 13(b); [135]). Muscle fibers can reversibly contract by up to 50% in isolation and 30% during natural movements. Muscle fibers are composed of mitochondria, which supply the sarcomeres with energy for contraction in the form of adenosine triphosphate (ATP), and parallel subunits called myofibrils (figure 13(c)), typically about 2 μm in diameter, which extend from one end of a muscle fiber to the other and consist of longitudinally repeated units called sarcomeres. The scalability property allows biological muscles to function as actuators at scales ranging from micrometres (sarcomeres) to meters (elephant trunks). The sarcomere is the functional unit of actuation in biological muscles (figure 13(d)). This core unit contains thick and thin filaments packed at high density into a nearly crystalline lattice [136]. The high specific work and power of muscles comes largely from the dense packing of actin and myosin proteins into muscle sarcomeres. The thin filaments (figure 13(e)) consist largely of actin, troponin and tropomyosin proteins. The thick filaments (figure 13(f)) consist mainly of myosin. The myosin protein has a pair of heads, 5 nm in diameter, which protrude from the thick filament backbone. Early studies from electron microscopy demonstrated that the myosin and actin filaments slide past each other during muscle contraction [137, 138]. Later studies showed that myosin heads form cross bridges with adjacent thin filaments during muscle contraction. Swinging of myosin cross bridges attached to actin associated with hydrolysis of ATP was identified as the mechanism of filament sliding [139, 140], and was consistent with a simple model linking muscle energetics and mechanics [141].

3.2. Actuation mechanism

When an action potential, generated by a motor neuron in the brainstem or spinal cord, arrives at a muscle fiber, a burst of Ca^{++} is released from the sarcoplasmic reticulum. The Ca^{++} binds to troponin, which rotates the tropomyosin molecule to expose sites on the thin filaments to which cross bridges can bind. Rotation of the myosin heads, initially charged with ATP, pulls the thin filaments toward the thick filaments [142], resulting in actuation via muscle contraction. As the myosin heads rotate, they generate tensile force from the chemical energy released as ATP splits into ADP (adenosine diphosphate) and Pi (inorganic phosphate). The ADP and Pi are then released from the myosin head, and the cross bridge remains bound to the thin filament until a new ATP molecule binds to start the cycle over again. The total force generated by a muscle is determined by the number of attached cross bridges. However, the number of cross bridges that can attach to actin at a given instant depends on muscle length, the so-called 'force–length

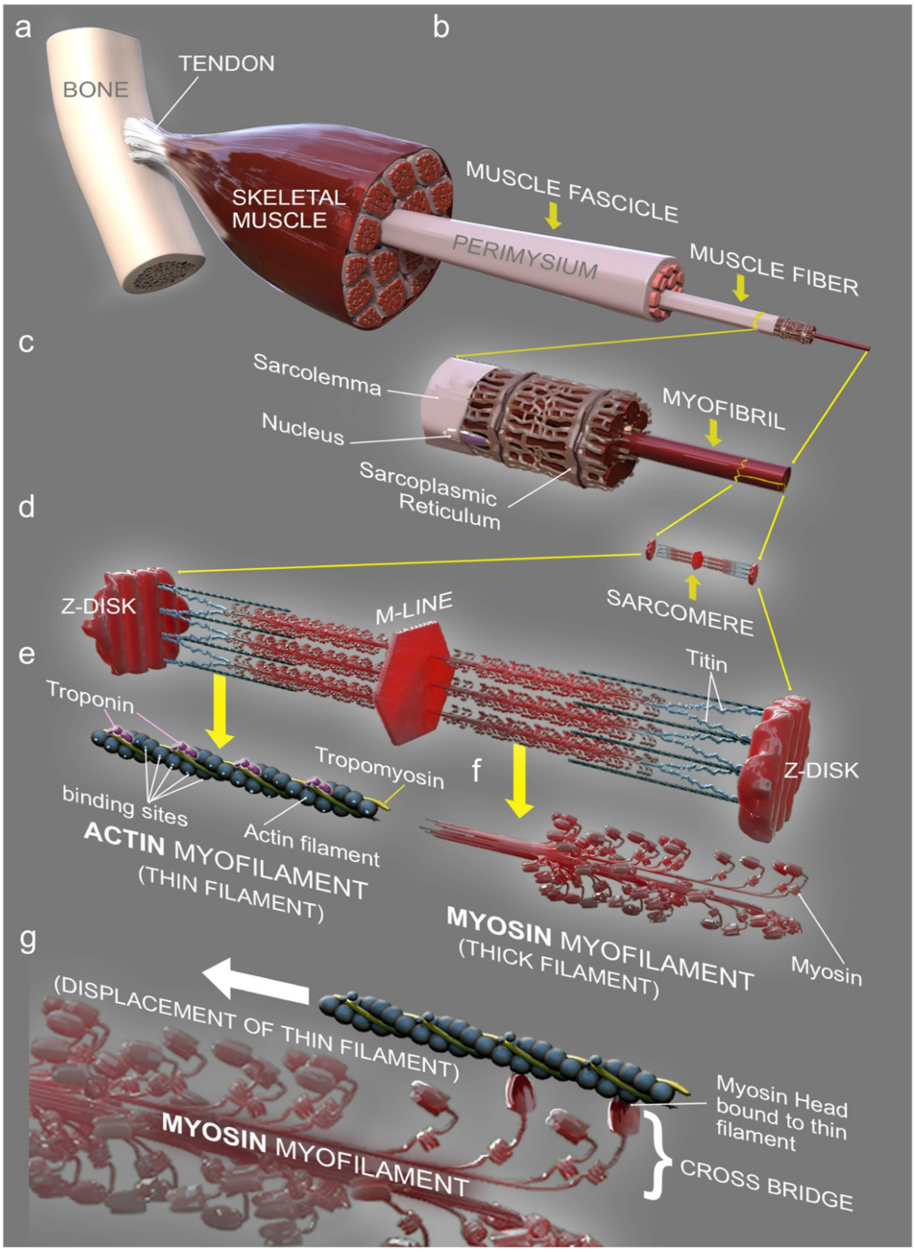

Figure 13. Structure of biological muscles. (a) In vertebrate animals and humans, skeletal muscles are connected to bones via tendons. (b) Most of the cross-sectional area of muscles is composed of muscle fibers consisting of numerous sarcomeres (c) arranged in series. (d) Sarcomeres are organized into near-crystalline arrays of actin (e) and myosin (f) filaments. (g) Displacement of the thin filament. Figure produced by Victor O Leshyk.

relationship' [143]. As sarcomeres are stretched, overlap between thick and thin filaments is progressively reduced. Cross bridge attachment also depends on the availability of Ca^{++}, which increases in response to an action potential and 'activates' the thin filaments. The sliding-filament swinging-crossbridge theory of muscle contraction led to the view of muscles as motors that produce a force when activated; analogous to how an electric motor, given an input voltage, produces a torque [144] or how elemental units of cavatappi artificial muscles or twisted polymer actuators generate a torque when internally pressurized or heated, respectively [117, 178]. An important feature of biological muscles, not explained by traditional cross-bridge theories, is that their viscoelastic properties (stiffness and damping) depend not only on the level of activation, but also on strain history [145]. Muscles develop more force during and after active stretching (force enhancement), and less force during and after active shortening (force depression), than the 'isometric' force that develops at the same final length. Force enhancement and depression allow for instantaneous adjustments of muscle impedance during unexpected perturbations, such as stepping on a stone or into a hole, when a muscle's force and stiffness change instantaneously, long before reflex feedback or supervisory commands from the nervous system can change the level of muscle activation [43, 133, 134, 146]. The importance of strain history in muscle force production has led to the idea that a critical element might be missing from theories of muscle contraction and models based on them [147], specifically a viscoelastic element whose stiffness and free length depend on activation [52, 148]. Recent research suggests that the giant titin protein (figure 13(d)) is the missing tunable spring [52, 53, 147]. This giant protein forms a continuous fiber from one end of a half-sarcomere to the other and transmits cross-bridge forces from the myosin filaments to the actin filaments in the Z-disk [147]. New evidence demonstrates that titin binds to actin in the presence of Ca^{++}, increasing stiffness and decreasing equilibrium length [53]. This mechanism can explain the strain-history dependence of muscle force production [149] as well as the adaptive dynamic response of muscles to unexpected perturbations [43]. The emerging view of titin as a tunable viscoelastic element leads to a different view of muscle as an active, composite material that actuates movement by developing force in response to combined effects of activation—which tunes the muscle's viscoelastic properties—and deformation by applied loads caused by interactions with the environment [51]. From this viewpoint, titin is a viscoelastic element in muscle sarcomeres that computes, morphologically, the effects of activation and deformation. By using 'morphological computation' to adjust viscoelastic properties, titin plays an important role in tuning impedance and stabilizing unexpected perturbations. This view of muscle as an active material with tunable stiffness and equilibrium length [52] provides new ideas for bio-inspired design of soft actuators.

3.3. Control

Control of actuation by biological muscles occurs at three levels: (1) supervisory feedforward commands from the brain (supervisory control); (2) embedded control provided by sensory feedback loops, between proprioceptive length and force sensors in the muscles and tendons, and pattern-generating circuits in the spinal cord; and (3) the adaptive dynamic response provided by the tunable material properties of the muscles themselves. Neuromechanics is the study of how muscles, sense organs, motor pattern generators, and the brain interact to produce controlled movement under varying environmental conditions [42]. Accurate control and adaptability of movement result from direct coupling between the neural system and the muscles. These systems communicate by a series of transformations of information, from brain and spinal cord to muscles to body, and back to brain. The control depends on the transformation of information (transfer function) and, in turn, on the dynamic behavior of each subsystem. To better explain how the interplay between the neural and mechanical systems occurs at all levels of biological organization, we use the example of a 'goalkeeper catching a ball'. Our goalkeeper must accomplish many tasks to catch the ball, including running toward the ball, adopting a suitable position for catching the ball, and eventually catching the ball. All of these tasks involve the interplay between sensorimotor properties of the nervous system and mechanical properties of the musculoskeletal system during locomotion. The higher level supervisory functions plan the sequence of movements required to intercept the ball, whereas embedded control via feedback from length and force sensors in the muscles and tendons themselves [150] regulates mechanical impedance by coactivating antagonist muscles that actuate the same joint [42, 85], while the adaptive dynamic response via tunable compliance at the level of the muscle itself provides versatility and adaptability, for example associated with unexpected changes in terrain (e.g., when the goalkeeper steps on a bump or into a hole on the playing field).

Muscle synergy: whereas the brain plans sequences of movement relative to a goal or task, spinal reflexes and sensory feedback loops activate specific groups of muscles synergistically to produce a desired movement. A muscle synergy is a pattern of activation of a group of muscles that work together to produce a particular movement, such as knee flexion. For example, when the goalkeeper crouches to prevent a goal by the opposite team, the muscles at the ankle and knee joints that work together to flex the knee are activated in a particular pattern called a 'muscle synergy'. Reflex loops and central pattern generators in the spinal cord produce the synergies, which provide actuation timing and control of the group of muscles as a unit, which improves coordination and efficiency [151–156]. A single muscle can be part of multiple muscle synergies, and a single synergy can activate various muscles. Muscle synergy leads to a reduction in the dimensionality of muscle control, akin to asking an orchestra to play a particular song rather than telling each musician which notes to play. The force can also be modulated by varying the number of fibers that are activated in parallel (variable recruitment). This grading of force enables efficiency to be maximized over a wide range of loads and contraction velocities, in addition to enabling control of acceleration and force.

Morphological computation: in biological muscles, the giant titin protein enables the adaptive dynamic response of muscles by morphologically summing the effects of activation (i.e., commands from the nervous systembrain) and strain (i.e., deformations produced by interactions with the environment). These morphological computations underpin the embedded control which leads to the versatility and adaptability of biological muscles. As a result of this morphological computation, muscles have a tunable compliance. Compliance tuning is the way soft structures (natural or artificial) interact adaptively with their environment. Common examples include octopus arms—which can bend around objects, squeeze through small gaps, or stiffen selectively when used as a modifiable skeleton or strut—and elephant trunks function similarly to transmit high forces, for example when lifting a tree. Tongues in general and human lips are other examples. To perform these different functions, muscles have the ability to adapt their impedance (i.e., stiffness and viscosity) instantaneously when loading conditions change [42]. Returning to our example of the goalkeeper, morphological computation by the muscles themselves can be seen when the goalkeeper catches a soccer ball that contains high momentum. The adaptive dynamic response inherent in the tunable compliance of biological muscles will provide the arm of the goalkeeper with time-varying compliance to adapt the ball's impact and modulate its momentum. Low compliance of arm muscles would lead to a large impulse as the ball makes contact, providing less time to grasp the ball, while a very compliant arm would not bring the momentum to zero and stop the ball. Conventional actuators could perform similarly, when using fast feedback control, but would not benefit from the computational efficiencies achieved through morphological computation. By instantaneously adjusting their stiffness and damping, muscles perform more work when an obstacle is encountered in the path of movement, whereas more energy is dissipated (damping) when muscles are rapidly unloaded [132, 133]. The tunable material properties of biological muscles [52] provide adaptive control of impedance without requiring sensing or feedback [42, 43], in contrast to conventional robots in which the impedance of every joint output torque is typically sensed and controlled using feedback. In biological systems, muscle synergy, morphological computation and adaptive dynamic response offload some of the computations normally attributed to supervisory control, reducing requirements for sensing and information transfer, and thereby off-loading computational burden from the nervous system. Although this offloading is computationally efficient for the supervisory controller (brain), it is not without drawbacks. Training muscle synergies requires learning over developmental or evolutionary time scales. For example, human babies typically require two years of learning to develop the synergies necessary for walking and while most ungulate species are able to walk quickly after birth, eons of evolutionary learning bestow them with pre-programmed movement sequences. In both cases, the efficiency and adaptability inherent to biological muscles requires time to learn and points to learned actuation response as an important area for continued research in the field of soft actuation [157, 158].

3.4. Energy sources and temperature control

In biological muscles, actuator, power source (mitochondria), and fuel (ATP, creatine phosphate, glycogen) are found within the same structure, which more or less exempts organisms from carrying voluminous fuel reservoirs. This self-contained power source capability allows biological muscles to exhibit high overall specific work (0.04 kJ kg^{-1}) and power (0.28 kW kg^{-1}; [159]) since their power source weight is low compared to those of conventional and soft robotic actuators [26]. However, the energy source for work and power of biological muscles depends on the intensity and duration of activity [160]. For short duration, high intensity, anaerobic activities like sprinting, energy comes from onboard supplies of ATP and creatine phosphate, which can fuel cross-bridge cycling without requiring oxygen or glucose (onboard energy). As the duration of sustained activity increases, muscles depend increasingly on de novo ATP synthesis by mitochondria, which additionally requires oxygen supplied by the circulatory system, and glucose from breakdown of fat droplets and glycogen stored within the muscles or liver (off-board energy). If glycogen and fat stores become depleted, for example when 'hitting the wall' during a marathon race, glucose must be delivered from the circulatory system in addition to oxygen. The definition of metrics such as specific power, specific work, and even efficiency become less clear at the systems level. For example, the specific work, power metrics, and efficiency of isolated muscles is similar to the overall efficiency of human walking ($\sim$0.2–0.4) but the efficiency achieved during running is substantially higher ($\sim$0.5–0.65) due to increased storage and recovery of elastic energy by the muscles and tendons [161]. The circulatory system plays additional roles in removing waste products that accumulate during exercise, as well as in temperature regulation. When waste products, such as inorganic phosphate and lactic acid, accumulate in muscles faster than they can be removed by the circulatory system, muscles experience fatigue, a decline in force for a given level of activation [162]. Fatigue of biological muscles is a major limitation compared to artificial muscles. In addition to providing oxygen and fuel and removing waste products such as carbon dioxide and lactate, the circulatory system of animals also provides temperature control for muscles, which like conventional actuators and artificial muscles produce heat as a byproduct of oxidizing fuel. While muscles function well over a fairly wide range of temperatures [163], their function can decline rapidly if they become too hot or too cold. Like biological muscles, many soft actuators also exhibit temperature dependence of their actuation performance metrics (section 4.2).

3.5. Limitations of biological muscles as actuators

The length- and velocity-dependence of biological muscles and their slow actuation response times are often cited as limitations [164]. As noted previously, the force, work and power of biological muscles depends on their length and velocity [141, 145, 165]. Biological muscles produce maximum force at intermediate lengths that represent optimal overlap of the thick and thin filaments in muscle sarcomeres [143], and the force of biological muscles falls faster with shortening velocity than that of electric motors [19, 141]. In contrast, conventional actuators such as electric motors with feedback control can deploy a constant maximum torque and/or stress during actuation independent of their joint angle and are capable of maintaining useful stress and power as a function of velocity [15]. Additionally, conventional actuators are bidirectional and symmetric, in contrast to biological muscles. However, the asymmetrical function of biological muscles is critical to their versatility. They function as struts when their length is constant, as brakes or springs when stretched actively, and as motors or shock absorbers during active shortening. Models of biological muscle actuation have been shown to provide accurate predictions using springs and dampers. The combination of elastic and viscous elements makes them produce actuation forces slowly compared to electric motors under isometric (constant length) conditions. However, their response time depends on both strain and strain rate, decreasing during stretch and increasing during shortening [54], making biological muscles suitable for any application where fast actuation is required. Most electrical and fluidic soft actuators are built from viscoelastic materials with relatively slower actuation response times, but most of them can also perform fast actuation responses [71, 117].

4. Comparative study

The latest research conducted on the actuation of biological muscles [24, 166] sets standards useful for evaluating the actuation performance requirements of suitable muscle analogs. From the conventional robotic and soft robotic literature, it has been established that artificial muscle technologies need to meet several crucial prerequisites, such as flexibility (soft), durability, and light weight [19–21, 24, 27, 28]. However, soft actuators could also mimic other properties of biological muscles such as morphological computation, adaptive control, adaptive dynamics response, self-contained power source capacities (onboard energy), scalability, muscle synergy and variable recruitment [41, 42, 84, 85, 132]. This section focuses on those actuators presented from sections 2.1–2.3 because they present similar performance to biological muscles, and they have been investigated more in-depth regarding the matter of this work.

As engineered systems, soft actuators may even be able to outperform muscle in areas such as time response, specific power, efficiency, fatigue, aging, etc [167, 168]. However, the performance of soft actuators can vary widely depending on the conditions of operation. This section evaluates actuation performance for a set of conventional actuators, soft actuators, and biological muscles (section 4.1). We compare key metrics, including average and peak specific power, specific work, maximum actuation strain and stress, lifetime, power cost, actuation driver and magnitude, actuator and total efficiency, and response time. In section 4.2, we use the inherent properties of biological muscles to develop a comparative study of soft actuators and biological muscles. Section 4.2 presents the latest advances in the soft actuation field regarding self-sensing, modeling, adaptive dynamic response, morphological computation, variable recruitment and scalability, energy source and temperature control, and length and velocity dependence. Additionally, section 4.2 also briefly describes why conventional actuators cannot achieve such properties.

4.1. Performance metrics

For any soft actuator to qualify as an artificial muscle, it should achieve similar performance metrics to biological muscles. However, this is not the only requirement (see section 4.2). To contextualize their performance, soft actuators are compared to each other, conventional actuators, and biological muscles.

Table 1 compares non-dimensional and specific actuation metrics for some conventional actuators (electro-mechanical and piston-cylinder actuators), soft robotic technologies (see section 2), and biological muscles (see section 3). The metrics include average and peak specific power, specific work, maximum strain and stress, lifetime, material cost per power unit, activation method (driver) and magnitude, efficiency, and response time. Although the scope of this work is limited to the actuator system (see figure 3), table 1 also includes a ‘total-system efficiency’ metric that considers off-board energy storage to output work, as some literature only reports these values. For soft-actuators, this is the electrical energy to mechanical work conversion, and for biological muscles this is chemical free energy to mechanical work. Furthermore, for the reported actuator efficiencies, we distinguish whether efficiency has been collected during only contraction or for a full-cycle as well as their activation driver (hydraulic or pneumatic) for fluid-driven soft actuators (footnotes in table 1).

As a point of reference, electric motor and piston-cylinder actuators (table 1) have high specific power metrics, high efficiencies of 80% (excluding pneumatic piston-cylinder actuators), and actuation stress of 0.6 MPa [13, 15, 16, 170]. Many soft actuators also possess advantageous metrics (table 1). Electro-active polymers (EAPs) exhibit excellent metrics, including specific work and power, maximum actuation strain and stress, and efficiency [24, 61, 75, 172]. Earlier prototypes were prone to wear or damage as a result of dielectric breakdown when operating in high electric fields, which initially limited the lifetime of these actuators. However, recent EAPs have life spans up to millions of cycles [174, 175, 184]. It remains

Table 1. Comparison of metric for various conventional actuators (three first columns or blue columns), soft actuators (next eight columns or orange columns), and skeletal muscles (last column or green columns). Electro-mechanical actuators (EMA) [13, 16, 30, 169], hydraulic cylinder (HC) [16, 170, 171], pneumatic cylinder (PC) [16, 169, 170], electro-active polymers (EAPs) [24, 61, 75, 76, 172–175], carbon nanotube (CNT) [24, 25, 57, 64, 65, 69, 176, 177], twisted polymer actuators (TPAs) [178], pleated pneumatic artificial muscles (PPAMs) [86, 100, 106], flexible elastomers actuators (FEAs) [27, 99, 179, 180], fluid-driven origami-inspired artificial muscles (FOAMs) [181], origami-based vacuum pneumatic artificial (OV-PAM) [115, 116], cavatappi [117], hydraulically amplified self-healing electrostatic actuators (HASELs) [70, 71], and biological muscles [24, 159, 166]. Time actuation response is qualitatively evaluated using Harvey balls. Bolded metrics outperform those metrics of skeletal muscles.

Metrics	EMA	HC	PC	EAP	CNT	TPA	PPAM	FEA	FOAM	OV-PAM	Cavatappi	HASEL	Skeletal muscle[a]
Avg/Peak specific power[b] ($kW\ kg^{-1}$)	**0.3–5** /—	**20–200** /—	**2–20** /—	**∼0.4** **/0.1–0.6**	**∼0.1** **/0.27**	27 **/50**	**1** /—	**1** /—	**∼1** **/∼2**	0.02 /0.02	**0.8** **/1.42**	**0.36** **/0.59**	**0.05** **/0.28**
Specific work ($kJ\ kg^{-1}$)	—	**0.09**	**0.15**	**0.1–0.75**	**0.7–2**	**2.48**	**1.1**	—	**∼0.25**	**0.19**	**0.11–0.38**	**0.07**	0.04
Maximum actuation strain (%)	—	∼35	∼35	**>100**	∼5	**49**	38	∼30	**90**	**>90**	**∼50**	**∼45**	>40
Maximum actuation stress (MPa)	—	**50**	**0.7**	**5**	**26**	**∼100**	0.16	**∼1.5**	**∼0.6**	0.04	**∼0.70**	0.3	0.35
Power cost (USD/W)	∼2	∼0.02	∼0.03	∼7	$\sim 6.5 \times 10^3$	$\sim 3 \times 10^{-4}$	∼5	∼0.02	∼0.2	∼1.25	∼0.06	∼0.055	—
Actuator efficiency (%)	—	90–98	30–40	—	—	—	∼57[c,f]	25–46	59[d,f]	∼99[c,f]	∼45[d,f]	—	—
Total system efficiency (%)	**50–90**	**40–45**	3–4	**25–80**	∼0.5	∼1	∼5[c,f]	**11–23**	2–5[d,f]	16[c,f]	**10–22**[d,f]	**21**[d,e,h]	20–40
Driver	Electrical	Fluid	Fluid	Electrical	Electrical	Thermal	Fluid	Fluid	Fluid	Fluid	Fluid	Electrical	Chemical
—	—	—	—	—	—	—	—	—	—	—	—	—	—
Magnitude	6–80 V	20 MPa	0.8 MPa	1.6 kV	0.1–10 V	25–250 C	0.4 MPa	0.2–0.5 MPa	−80 kPa	−80 kPa	−1.8 MPa	5–10 kV	—
Lifetime (cycles)	$\sim 10^4$	$>10^6$	10^6	$\sim 10^6$	$\sim 10^5$[g]	$>10^6$	$>10^5$	$\sim 10^6$	$>10^4$	—	$>10^4$	$>10^5$	$>10^9$
Time actuation response	●	●	◕	●	●	◔	◕	◕	◕	◑	●	●	◕

[a]Skeletal muscles specific metrics include the weight of auxiliary components (onboard energy source and sensors).
[b]This value is limited to the energy rate provided by the energy source.
[c]Pneumatic.
[d]Hydraulic.
[e]Full-cycle analysis of actuator efficiency (includes energy recovery).
[f]Actuators' energy conversion contractile efficiency (without energy recovery).
[g]33% reduction in strain.
[h]Efficiency for a donut-HASEL.

uncertain whether DEAs can achieve a lifespan of billions of cycles as biological muscles do. Carbon nanotubes (CNT) have maximum actuation stresses of 26 MPa, actuation response times <10 ms, strain rates of 19%/s, and specific power of 0.270 kW kg^{-1} [25, 64, 65]. However, they exhibit low strain (∼3%) and low total efficiencies (0.5%), which are key factors in developing suitable artificial muscles [24, 176]. Additionally, CNTs are difficult to extract and fabricate, which makes this technology expensive (high purity samples cost about $750 g) [69]. As a basis of comparison, TPAs and cavatappi cost about $0.005 g and $0.05 g, approximately 100 000× and 10 000× less expensive, respectively. HASELs can generate high strains (∼60%) and full-cycle system efficiency of 21%. Twisted polymer actuators (TPAs) develop specific work of 2.5 kJ kg^{-1} and average specific power of 27.1 kW kg^{-1}. However, thermal activation requirements limit their response time, control, and efficiency [90, 178]. The electrical-mechanical energy conversion efficiency for TPAs is thought to be similar to that of shape-memory metals, which is approximately 1%–2% [178].

Fluid-based actuation has been investigated extensively for the last 70 years and is a potential candidate for significant applications in human-mimetic robots. McKibben actuators, the grandfather of muscle-like fluidic actuators, are pneumatically or hydraulically driven artificial muscles (PAMs or HAMs) widely used in robotics and wearables [104, 185–187]. Pleated pneumatic artificial muscles (PPAMs) are a recently improved embodiment of conventional McKibben actuators that can develop a specific work of 1.1 kJ kg^{-1} and contractions of 38% [86, 106]. The design of PPAMs has also improved efficiency by limiting frictional losses and actuation hysteresis characteristic of conventional McKibbens. However, all McKibbens suffer from inefficient volumetric growth during inflation limiting parallel operation and scaling.

Due to the muscle-like response of McKibbens, other fluid-driven soft actuators have been developed and investigated with the goal of better emulating the properties of biological muscles. Flexible elastomer actuators (FEAs) generate contractions up to 28%, blocked forces of 10 N, and specific power of 1 kW kg^{-1} [27]. FEA metrics depend on their configuration, and they can be programmed and designed to achieve specific metrics. Origami-based vacuum-actuators have also been developed for soft robotic applications. Fluid-driven origami-inspired artificial muscles (FOAMs) develop contractions of up to 100% and have a mechanical-to-mechanical energy conversion efficiency of 23% and 59% when pneumatically and hydraulically tested, respectively. However, similar to biological muscles, the large contractions by FOAMs significantly decrease with small load increments [181]. Although not as drastically in FOAMS, the force of most soft actuators (DEAs, CNTs, TPAs, PPAMs, FEAs, cavatappi, and HASELs) typically depends on length and velocity [71, 117, 181, 188]. The related origami-based vacuum pneumatic artificial muscles (OV-PAMs) solve the previous strain–stress ratio limitation of FOAMs by maintaining a strain close to 100% while generating maximum force. However, OV-PAMs are voluminous, limiting their implementation in small applications [115, 116]. Finally, cavatappi were conceived as a hybrid of twisted polymer actuators and McKibbens [117]. The metrics of cavatappi exceed those of biological muscles (table 1). However, cavatappi require a micro-pump along with a battery as energy sources, leading to an increase in total system weight, hindering but not preventing their implementation in portable applications. Finally, and this is true for all soft actuators, the time response depends on the power source, system, and energy deployed for actuation. With this consideration, in table 1, we report a qualitative assessment of time response based on their actuation drivers.

Compared to biological muscles, conventional and soft actuators (table 1) can actuate for a high number of cycles (life-span) without sacrificing performance, accuracy, and repeatability (CNTs are an exception). In contrast, biological muscles suffer from fatigue when they are cyclically actuated, leading to a drop in performance [189].

At first glance, various soft actuators achieve or even outperform metrics of biological muscles (table 1). However, unlike the soft actuators' metrics, the metrics for biological muscles also more or less account for the weight of auxiliary components like power source (ATP or onboard energy) and sensors (proprioceptors), which could lead to an improvement of the specific metrics of biological muscles compared to soft actuators. It is crucial to clarify that soft actuators mostly use off-board energy sources for actuation; thus, conducting an exhaustive comparison between soft actuators and biological muscles specific metrics is not realistic because the capacity to integrate onboard energy sources in soft actuators architecture is still very limited. Additionally, specific values for metrics that account for the weight of energy sources and sensors of soft actuators are largely unreported in the literature.

Figure 14 shows a graphical representation of some of the metrics presented in table 1. The actuators are grouped into three categories; conventional, soft, and biological muscles. Performance varies widely within these categories; however, correlations are found when looking at the driving mechanisms. Thermally driven and ion transport actuators (TPAs and CNTs, respectively) have low efficiency and high maximum stress. Pneumatically driven actuators exhibit average maximum stress and strain, efficiency, and specific power. These actuators normally fall inside the muscle performance region (figures 14(a) and (b)). Hydraulically and electrically driven actuators

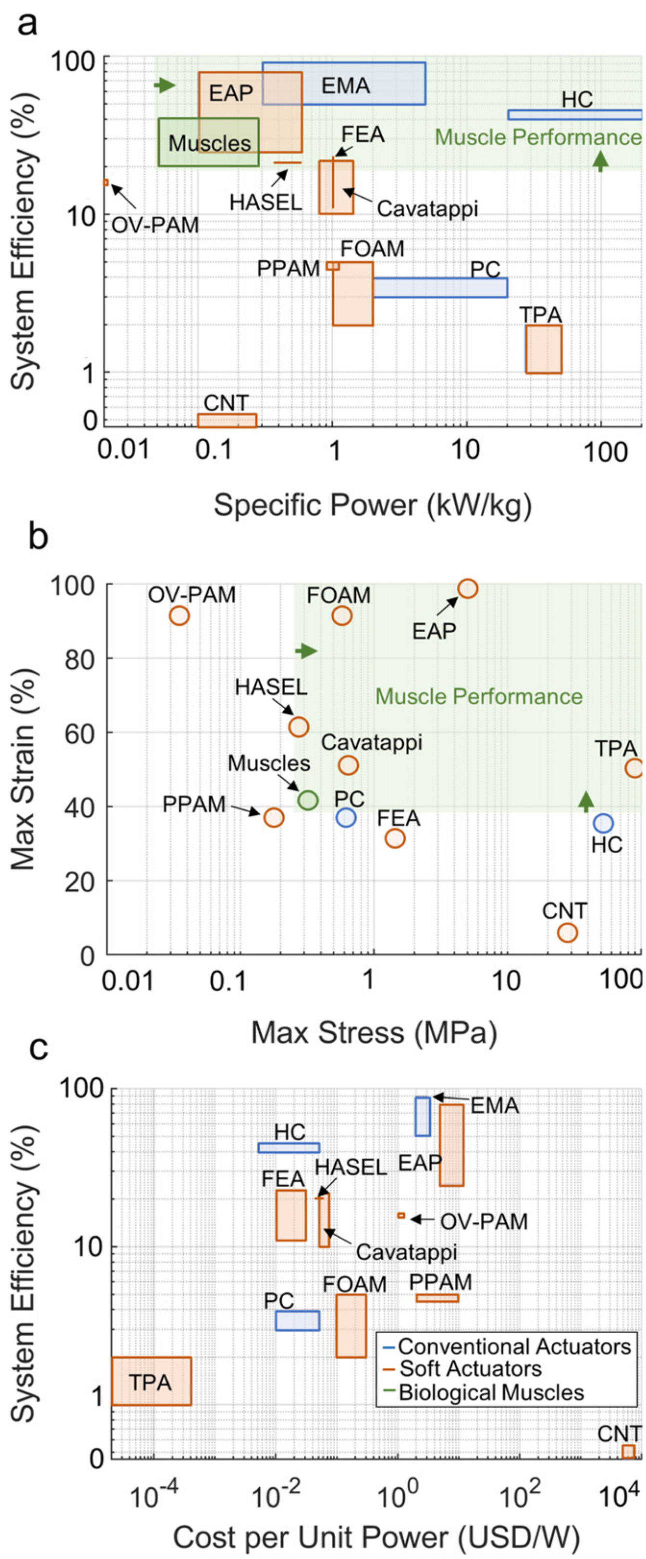

Figure 14. Comparison of selected metrics of conventional actuators, soft actuators, and biological muscles. (a) System efficiency versus specific power. (b) Maximum strain versus maximum stress. (c) Efficiency versus cost per unit power. In figures (a) and (b), the green area indicates the performance region of biological muscles.

have higher maximum stress, efficiency, and specific power than pneumatically driven actuators, and they fall into a performance region located to the top-left from skeletal muscles. Finally, in terms of their efficiency versus cost-per-unit-power relationship, most actuators are found in the center region of the plot (figure 14(c)) and can be considered inexpensive technologies. TPAs fall to the bottom-left of the plot as a result of low efficiency, and CNTs fall to the bottom-right due to their high extraction cost.

4.2. Control and properties

The unique properties of biological muscles allow these living actuators to respond adaptively to perturbations by virtue of their embedded control, which off-loads computation from the brain via morphological computation, and onboard energy. Here, we investigate how soft actuation technologies emulate these properties. This section compares current soft actuation technologies to biological muscles in terms of control, self-sensing capabilities, modeling, tunable compliance and damping, variable recruitment, morphological computation, energy sources and temperature regulation, and length and velocity dependence.

4.2.1. Control strategies

Unlike conventional robots, biological organisms have evolved to survive in environments characterized by rapid changes, high uncertainty, and limited information. Although conventional robots display highly repeatable and accurate actuation, a remaining challenge is to endow them with adaptive dynamics that would maintain stability and control in response to unexpected perturbations. Many roboticists have used advances in computation and data analysis to overcome this drawback in conventional actuators [11, 190–195]; however, actuators that can adjust their dynamic behavior would aid this effort. A new trend is to use ideas from biology and self-organizing systems to inform the design of dynamically adaptive robots [23]. Although many challenges remain, bio-inspired robotics will eventually enable researchers to engineer robots and actuators for the real world that will perform like biological organisms in adaptability, control, versatility, fast-response, and agility. Similar to biological muscles, actuator control can occur at three levels: (1) supervisory feedforward commands from an external control module (brain in a biological system) to process sensed information, generate an output by actively adjusting the actuator dynamics, and even learn from experience [42, 196, 197]; (2) sensory feedback loops between proprioceptive length and force sensors in the actuator architecture; and (3) adaptive dynamic response provided by the passive tunable material properties (compliance and impedance) of the soft actuators themselves (morphological computation). The supervisory and embedded (feedback) control strategies will depend on the actuator's modeling, self-sensing capacities, tunability of the elements, variable recruitment, and morphological computation [198].

Self-sensing: several soft actuators have self-sensing or partial sensing properties, including CNTs, TPAs, EAPs, FEAs, McKibbens, FOAMs, and HASELs. CNTs with graphite-carbon nanotube hybrid films [199] have used decoupling of electrothermal stimulus and strain sensation to provide real-time feedback [199–202]. Another strategy is to combine CNT films sandwiched between two polydimethylsiloxane (PDMS) layers that function as a self-sensing soft actuator [201]. Twisted polymer actuators also integrate self-sensing abilities, including closed-loop control through self-sensing of joule-heated TPAs based on inductance [203]; adding conductive and stretchable nylon strings into TPAs to estimate strain from resistance [204, 205], or even integrating stretchable optomechanical film sensors into TPAs, which provides a simple strategy for dynamic strain sensing [206]. The predominant sensing mechanism of EAPs uses the actuator-sensor reversibility property; a sensor-actuator design is coupled in a parallel configuration to create self-sensing [207, 208].

Fluidic elastomer actuators (FEAs) also have the capacity for proprioception. FEAs with flexible or stretchable sensors within the soft bodies feature self-sensing with limited hindrance to motion. Different sensing technologies have been used, including resistive, magnetic, capacitive, optoelectronic, and even conductive working fluids [112, 209–211]. Although sensors have not been integrated into PPAMs, McKibbens have embedded microfluidic sensing [212]. The McKibben was composed of three main components: an elastomer air chamber, embedded Kevlar threads, and a helical microchannel filled with a liquid conductor. During contraction, the microchannel can detect the shape change of the actuator by sensing the expansion of the air chamber. FOAMs were built with a nylon-based linear zigzag actuator (60-degree folds) with a reflective optical sensor (TCRT1000, Vishay semiconductors) attached on its skeleton [181]. This optical sensor reads the distance between the two plates of one fold, which is used as a contraction sensor for the linear configuration. Finally, HASELs also serve as strain sensors and actuators simultaneously. The equivalence of HASELs to a resistor–capacitor circuit allows them to transiently measure the capacitance directly related to the actuation strain [71]. Most soft actuators are compatible with sensor integration. For example, cavatappi could take advantage of some of the sensing techniques used in other soft actuators, like stretchable optomechanical film sensors in TPAs or conductive working fluids in FEAs. Many soft actuators could sense by coactivating antagonist actuators similar to biological muscles [84]. In addition to strain sensing, self-sensing capabilities also include force sensing (similar to biological muscles), which could be achieved using material models. In terms of implementation, most of these sensing techniques have been characterized, modeled, and used in close-loop control strategies, facilitating the estimation of deflection and force [181, 203, 205, 207, 211]. This has helped to lay a foundation for control using the integrated sensing properties of soft actuators and provides insight for controlling untethered soft robots.

Modeling: in contrast to conventional actuators made from rigid components, soft actuators are fabricated from soft materials like polymers, whose properties are usually challenging to characterize and model. These soft materials can be sensitive to external environmental factors such as temperature, humidity, or UV light [95, 213, 214], which can encumber accurate models for actuation predictions. Additionally, most of the soft actuators discussed here are viscoelastic [215, 216]. While the time-dependence of viscoelastic materials adds complexity to models, this viscoelastic behavior provides soft actuators with the potential benefits of tunable-element actuators and potentially adaptive dynamic response. This may enhance other advantageous properties such as tunable compliance and impedance, energy absorption (using passive mechanical dynamics), and morphological computation as in biological muscles. These features can significantly improve control and the capability of soft robots to adapt to unexpected perturbations [217–219]. Despite the modelling challenges discussed above (temperature, humidity, and UV light dependencies), initial quasi-static and dynamic material-based models have been achieved for DEAs [32, 220], CNTs [221], TPAs [222–224], PPAMs [87, 100], OV-PAMs [115], and FOAMs [225].

When modeling the motion of soft robots, two different strategies have been used, depending on the type of application: (1) articulated robots actuated with contractile soft actuators; and (2) continuum soft robots with multiple degrees of freedom (continuum soft actuators). Contractile actuators are normally deployed in articulated robots that use kinematic linkages (rigid bodies) to couple multiple joints together, similar to the skeletons of vertebrates. The actuation response of single DOF contractile soft actuators usually mimics biological skeletal muscles (EAPs, CNTs, TPAs, PPAMs, FOAMs, OV-PAMs, cavatappi, and HASELs). The similarities of articulated applications of soft robots with those of conventional robots have led to modeling control schemas of low and mid-level operating spaces, using inverse kinematics and dynamic operations as the basis for classical rigid robotic models [226–233].

Applications where the entire robot body is a soft deformable material capable of multiple degrees of freedom (FOAMs, HASELs, EAPs, and FEAs), like an octopus (invertebrates) present many challenges [111, 112, 183, 234]. For these cases, conventional robotic models are not suitable because of the continuum nature of these actuators, which makes it unclear how to represent the state variables, dimensions of design, and parameters at different body postures of the systems. Thus, continuum mechanical models are necessary. Although control models for these systems are very challenging to develop and implement, these actuators' advantages and muscle-like behavior are pushing researchers to find innovative bio-inspired continuum solutions to model and control these soft-bodied robots [157, 198, 233, 235–241].

Adaptive dynamic response: although most materials used for soft actuators are inherently compliant, they also allow variations in compliance and, often, damping, meaning they can perform adaptive dynamic actuation [12, 27, 242]. This property is a requirement in safe HMIs [12, 14, 27, 28, 243–246] and is one of the principal motivations for creation of soft robots. The capacity of soft actuators to tune their compliance and impedance allows for adapting their dynamics during actuation and yielding power and control to the human when necessary. Furthermore, and similar to biological muscles [52], they allow deviations from the equilibrium position depending on the applied external force, allowing modulation of load capacity.

Although conventional actuators can also achieve tunable compliance using rapid feedback control loops, this adds complexity to the system. Moreover, feedback control only works correctly if the actuator bandwidth is adequate to the applications' conditions [247, 248]. For this reason, compliant soft actuators, made from flexible materials such as polymers with similar elastic and rheological properties to soft matter found in nature, have been designed to make HMIs safer and improve control [249, 250].

The system's equilibrium position depends on the combination of the equilibrium positions of the constituent elements, so in some cases, it is possible to actuate the individual units while leaving the whole system at rest. This feature allows independent control of the compliance, damping, and equilibrium position of the system. The soft actuators presented in section 2 have been implemented in this antagonistic-agonist configuration to modulate the joint compliance or just in applications where variable compliance was required. Variable compliance is normally a property of most soft actuators as they have in common that their actuation response is a result of changes in the compliance of their soft material or structure.

Dielectric elastomer actuators (DEA) have been laid out in a series of counter-opposed configurations to achieve variable compliance without shifting the equilibrium or zero force point, and even variable damping when using a variable capacitance connected between the counter-opposed DEAs to resist motion by dissipating electrical energy (see figure 15 bottom-right diagram); [79]). Additionally, DEAs have been deployed in dynamic hand splints for rehabilitation to help patients affected by motor disorders of the hand and have residual voluntary movements of fingers or wrist. DEAs have also been used in active orthoses that allow for real-time control of the training exercise by modulating the mechanical compliance [243]. Although PPAMs are challenging to arrange in parallel and are less flexible than many other soft actuators, they have been used in a compliant antagonist-agonist actuator configuration for walking and running robots. The variable compliance provided by PPAMs in these applications contributes to absorbed and softened impacts during walking and effectively stores and releases energy during the phases of bending and stretching [100]. FEAs were fabricated with different modes of actuation using integrated adjustable compliance layers. Each layer was provided with a microheater and thermistors to modulate its temperature and stiffness, which allowed tunable compliance of the overall actuator [251]. Although not mentioned in their work, the adjustable temperature potentially allowed for changes in damping. Soft actuators configured in a helical shape such as TPAs and cavatappi inherently provide tunable compliant features due to their variable spring design [60, 90, 117, 176–178, 252]. Twisted and coiled polymer actuators have been combined with silicone skin in a compliant haptic finger wearable device to provide lateral skin stretch sensations [253] or even used as twisted string actuators (TSA) to increase their compliance and maximum strain [204]. Finally, straight carbon nanotubes have been combined with dielectric elastomers made from PDMS and carbon grease to create compliant electrodes with large deformation under applied voltage [254].

The capacity to rapidly tune an actuator's dynamic response can also improve performance and efficiency in activities like walking [257, 258], running [259], and jumping [260]. The ability of muscles and tendons to act as springs enables storage and recovery of strain energy which saves metabolic energy. The benefits of this property in biological muscle have also led researchers to promote the addition of elastic elements in conventional robots to increase efficiency [261, 262]. This property could also be exploited in soft actuators [83, 117, 263, 264].

Actuators differ in terms of their tunable compliance and damping (see figure 15). Conventional actuators have null tunable compliance and damping compared to biological muscles with high tunable compliance and damping, representing the spectrum of adaptive dynamics. In figure 15, starting from the bottom-left, moving up leads to higher tunable compliance and moving right to higher tunable damping; the goal being to achieve the adaptive dynamics represented by biological muscles. Improving the muscle-like tuning of soft actuators will benefit bioinspired applications and robotics, including wearable haptics in gaming, health, virtual reality, prosthetics, and humanoid robots.

Morphological computation: biological muscles reduce the computational burden of the control system (brain) by using the adaptive dynamic response of the muscles themselves when external perturbations occur in an uncontrolled environment [42, 158, 219, 265]. This property has been defined as morphological computation and is an inherent property of biological muscles that simplifies control.

One of the fundamental control problems of rapid locomotion in conventional walking or running robots is that feedback control loops are too slow to adjust the system when quick perturbations occur. As morphological computation sidesteps this shortcoming, conventional actuators implemented this property by adding elastic elements. This addition contributed to exploiting interaction with the environment for rapid passive adaptive dynamics [158, 219, 265]. The morphological computation in these cases was the result of the complex interplay among agent morphology, material properties (in particular the added springs), control (amplitude, frequency), and environment (friction, shape of the ground, gravity).

To develop robotic technologies that can share the rapid adaptability benefits of biological muscles, morphological computation becomes another important property in novel artificial muscle technologies. The main advantage is that complicated control architectures can be simplified using highly tunable element actuators (soft actuators), and interactions with objects or the environment derive from the passive tunability of the agent itself. Furthermore, to feature morphological computation in soft robotics, the soft actuation technologies must be purposely designed to meet specific requirements such as mechanical properties, morphological design, high integration of components (sensors and actuators), which push soft robotics technologies forward [266].

Morphological computation and tunability of soft or flexible materials has been used in robots to simplify control tasks that involve adapting to unstructured environments [255, 267–270]. An octopus-like robot capable of mimicking the real octopus arm behavior is one example of morphological computation in soft robotics [271–273]. These robots use a system of contractile shape memory alloy springs and motor-driven tendons that are capable of adaptation. The soft nature of the robot allows the arms to change their mechanical properties and exert forces on the environment. The soft octopus-like arm has been shown to implement motor control primitives (such as the ones found in the real octopus), which, together with the geometrical shape of the arm, demonstrated the possibility to perform effective and energetically efficient movements with a low computational burden.

Another example of morphological computation by soft robots involves soft lithographic microactuators. The microactuators combine conducting polymers to provide the actuation with spatially designed structures for a morphologically controlled, user-defined actuation. Soft lithography was employed to pattern and fabricate PDMS layers with a geometrical pattern for use as a construction element in the microactuators. These microactuators achieve multiple bending motions from a single fabrication

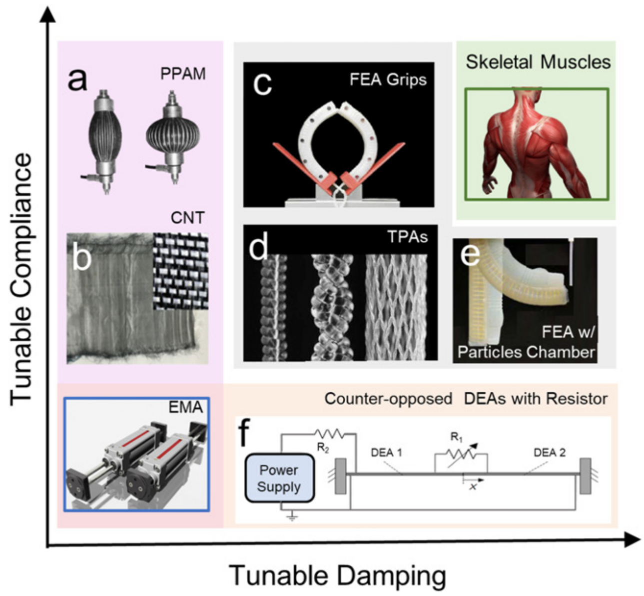

Figure 15. Progress and future directions in tunable compliance versus damping. Actuators as a function of their capacity to tune compliance and damping. (Left) Soft robots with tunable compliance that increases from bottom to top. [86] 2012, reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com.) [59] John Wiley & Sons. (Middle) Soft actuators with tunable compliance and damping, from left to right and top to bottom. Reproduced from [255]. CC BY 4.0. From [178]. Reprinted with permission from AAAS. © [2018] IEEE. Reprinted, with permission, from [256] (Bottom) Soft robots with little or no tunable compliance that increase their tunable damping capacities from left to right. (Top-right-corner) High adaptive dynamic level of biological muscles and goal for soft actuators. Reprinted from [79], Copyright (2008), with permission from Elsevier.

process, depending on the morphological pattern defined in the final step [270].

This soft robot application shows how morphological computation can be used with soft actuators. Here, the mechanical properties of the materials and geometrical design are used to passively tune compliance and damping to simplify the system control behavior. Although morphological computation has been primarily investigated in soft continuum actuators using spring-shape memory alloys and soft lithography microactuators, there is no reason to think that similar spring-shape soft actuators presented in section 2, such as CNTs, TPAs, and cavatappi, or soft continuum actuators such as FEA, HASELs, and FOAMS could not feature morphological computation.

Muscle synergy, variable recruitment, and scalability: pattern generators in the spinal cord can activate specific muscle groups synergistically to achieve desired movements and reduce control dimensionality [151–156]. The concept of synergy has been successfully implemented in conventional robotic control models [274–277]. These new control methods improve control of robots with high degrees of freedom. Although these control strategies require complex algorithms and computational cost, they are based on neural-engineering principles and show promise for use in soft robots. Artificial muscles share many biological muscle properties such as adaptive dynamic response, morphological computation, and element tunability, which will be advantageous when using muscle synergy-based control models. To perform variable recruitment, soft actuators require the capacity for fabrication at small scales (scalability), like biological muscles, allowing parallel arrangements.

CNTs, TPAs, thin McKibbens, FOAMS, cavatappi, and HASELs can be fabricated and maintain their performance metrics over a range of scales, and like muscle fibers, can be arranged in series and/or parallel [70,71,178, 117]. Series arrangements amplify strain and strain rate, whereas parallel arrangements increase contractile forces and allow for variable recruitment. Several design features of soft actuators can interfere with or prevent deployment in parallel arrangements, including large volumetric changes during actuation (PPAMs) [87] or heat transfer in TPAs that requires isolation or wide spacing between actuators [278].

Variable recruitment has been studied extensively on McKibbens [106, 279–285]. As an attempt to mimic the selective recruitment of motor units in a human muscle, a variable recruitment control strategy was implemented using a parallel bundle of miniature McKibben actuators [282]. This bioinspired control strategy allowed muscle bundles to operate the fewest miniature McKibbes necessary to achieve the desired performance objective, improving the operating efficiency while also increasing force generation and displacement [282]. Additionally, a passive recruitment control approach using McKibben actuators was investigated [283]. This approach used a uniform applied pressure to all McKibbens while creating differential pressure responses and threshold pressures via tailored bladder elasticity parameters. They developed a model that uses elastic bladder stiffness to control an artificial muscle bundle with a single valve. This control strategy was compared to a bundle of McKibbens with both low and high threshold pressure units and a single fluidic artificial muscle of equivalent displacement and force capability. The results of this analysis indicate the efficacy of using this control method; it is advantageous in cases where a wide range of displacements and forces are necessary and can increase efficiency when the system primarily operates in a low-force regime but requires occasional bursts of high-force capability [283].

Although variable recruitment control strategies have mostly been investigated for PPAMs, there is no reason to think that other actuators that allow for parallel arrangements could implement similar variable recruitment techniques. Moreover, with PPAMs, the arrangements were voluminous, limiting the bioinspired applications at the human scale; however, this limitation could be mitigated by using other soft actuators.

4.3. Energy sources and temperature regulation

Biological muscles integrate onboard energy sources in ATP, creatine phosphate, and glycogen, allowing for short-duration actuation, but also use off-board energy sources outside the muscle for long-duration actuation. In a similar manner, when directly compared to biological muscles, artificial muscles could integrate onboard energy sources for short duration actuation. Although FEAs have onboard energy capabilities using catalyzed chemical decomposition of hydrogen peroxide [99, 289] and FOAMs can add solar panels and electronics to the skeleton [181], onboard energy has not been extensively implemented in soft actuators. In this section, we review the most promising methods to integrate onboard energy in soft robots. In doing so, we distinguish the different actuators in terms of their energy input (activation mechanism) and focus on fluid-driven and electro-activated actuators. We also briefly review off-board energy sources of soft actuators for long-duration actuation. Finally, in this section, we also review one more energy aspect of biological muscles and soft actuators; temperature control a.k.a. thermoregulation. Temperature regulation plays an essential role in controlling soft actuators as their actuation response and performance is temperature-dependent, and temperature changes are unavoidable in unstructured environments.

Fluid-driven actuators such as FEAs, PPAMs, and cavatappi are usually activated using external high-pressure tanks or portable pumps/compressors along with batteries [114, 117, 290, 291–293], while OV-PAMs and FOAMs require vacuum pumps for portable applications [115, 181]. In contrast, electro-activated soft actuators such as HASELs, TPAs, EAPs, and CNTs portably operate with just external batteries [83, 294]. These well investigated and widely used conventional energy sources are normally too large to be integrated into the actuator architecture. Onboarding energy in the actuator architecture would augment the degree of integration, decrease actuation time delay, and avoid cumbersome auxiliary components.

Although many chemical pressure generation methods are candidates for achieving onboard energy sourcing in fluid-driven soft actuators [295, 296], catalyzed chemical decomposition of hydrogen peroxide is the most promising method as it can quickly deploy a wide range of pressure (from 0 to 30 MPa) while keeping a high volumetric flow and specific energy density [296]. This method releases energy through exothermic chemical reactions in the presence of a catalyst. The decomposition of hydrogen peroxide produces an increase in pressure in the actuator, which allows for powering portable mobile soft robots [99, 289, 297, 298]. Stretchable microsupercapacitors have been used as onboard energy sources in electro-activated soft actuators. These are promising candidates due to high power density, miniaturization, and feasibility of embedding in the actuator architecture [299]. Figure 16 shows the progress of self-sensing versus onboard energy integration in the field of self-contained soft actuation. Here, the left column shows soft robots with low onboard energy integration and the bottom soft robots with low self-sensing capabilities. Self-sensing and onboard energy increases when moving toward the top-right corner of the graph.

Finally, developing soft actuators that can perform homeostasis similar to biological systems is crucial to improving functionality and efficiency in unstructured environments [301]. One key factor is thermoregulation. Generally, most soft materials (polymers) used for soft actuators are temperature sensitive, leading to changes in properties, performance, and time-variant dynamics which could reduce feedback control performance. Although changes in the actuation response due to temperature could be modeled, these models would be complex, resulting in cumbersome control strategies. A thermoregulation technique has been proposed using passive perspiration in 3D-printed hydrogel actuators [302]. The chemomechanical response of the hydrogel materials used for fabrication was such that, at temperatures below 30° C, the pores were sufficiently closed to allow for pressurization and actuation. In contrast, at temperatures above 30° C, the pores dilated to enable localized perspiration in the hydraulic actuator. These sweating actuators exhibit a 600% enhancement in cooling rate (i.e. 39.1° C $\min^{-1}$) over similar non-sweating devices. Combining multiple finger actuators into a single device yielded soft robotic grippers capable of mechanically and thermally manipulating various heated objects. The measured thermoregulatory performance of these sweating actuators (~107 W kg^{-1}) dramatically

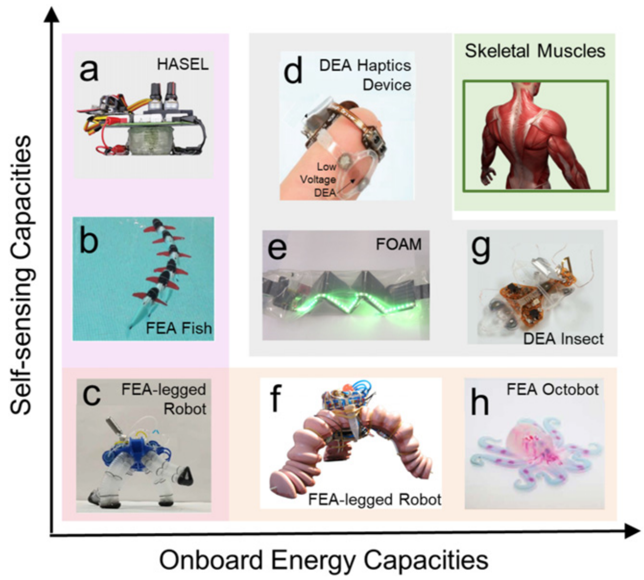

Figure 16. Progress and future directions in self-sensing versus onboard energy integration. Autonomous soft robots and actuators as a function of their level of self-sensing and onboard energy integration. (Left) A range of soft robots with low levels of onboard energy integration and self-sensing capacities that increase from bottom to top. [83] John Wiley & Sons. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature [300] Hydraulic Autonomous Soft Robotic Fish for 3D Swimming, Katzschmann, R. K., Marchese, A. D., and Rus, D., (c) 2016. From [290]. Reprinted with permission from AAAS. (Middle) Soft robots that merge onboard energy and self-sensing, from left to right and top to bottom. [287] John Wiley & Sons. Reproduced from [181]. CC BY 4.0. From [286]. Reprinted with permission from AAAS. (Bottom) Soft robots with little or no self-sensing capacities with increasing onboard energy integration from left to right. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature[99] An integrated design and fabrication strategy for entirely soft, autonomous robots, Wehner, M., Truby, R. L., Fitzgerald, D. J., Mosadegh, B., Whitesides, G. M., Lewis, J. A., and Wood, R. J., (c) 2016. © [2014] IEEE. Reprinted, with permission, from [288].(Top-right-corner) High onboard energy integration and self-sensing of biological muscles and goal for soft actuators.

Table 2. Qualitative evaluation and comparison of muscle and soft actuator properties using Harvey balls. The red border in Harvey balls indicates that those properties have been initially implemented in control strategies. (Note that conventional actuators are excluded as they are not the focus of this comparison).

Muscle properties	EAP	CNT	TPA	PPAM	FEA	FOAM	OV-PAM	Cavatappi	HASEL	Skeletal muscle
Onboard energy	—	—	—	—	●	◕	—	—	—	●
Temperature control	—	—	●	—	◕	—	—	—	—	●
Self sensing	●	●	●	●	●	◑	—	—	●	●
Tunable compliance	◕	◕	●	◕	●	—	—	●	—	●
Tunable damping	◕	—	◑	—	◕	—	—	◑	—	●
Morphological computation	—	—	◕	—	◕	—	—	◕	—	●
Length/Vel. force dependence	◔	◔	◔	◔	—	○	●	◔	◔	◔
Variable recruitment	◑	◔	◔	◔	—	●	◔	●	●	●

exceeded the evaporative cooling capacity found in the best animal systems ($\sim$35 W kg^{-1}) at the cost of a temporary decrease in actuation efficiency. In general, minimal research has been conducted on temperature control of soft actuators (except for thermally activated actuators), and further research will be needed to inform whether automatic perspiration mechanisms can be successfully used in other soft actuators. Similar to biological muscles, new materials used in soft actuators should have the capacity to sense and regulate their temperature.

4.4. Length and velocity dependence

From an actuation perspective, length- and velocity-dependence of biological muscles is considered as a limiting factor, as important metrics like stress, specific power, work, and efficiency vary with muscle length and velocity [141, 145, 165]. Conventional actuators such as electric motors can deploy a constant maximum torque and/or stress during actuation independently of their joint angle or position, and are still capable of maintaining useful stress and power as a function of velocity [15, 169]. Similar to biological muscles, the force of soft actuators usually depends on length and velocity [71, 117, 181, 188]. There are some exceptions, such as OV-PAMs, which can hold constant force/torque independently of length [115].

5. Conclusions

Soft actuators and robots have been an important focus of study in the last decades to improve HMI, for example in individuals with gait disorders, limited mobility, amputated limbs, or even augmented performance. In this review, we developed an understanding of progress in soft actuation technologies compared to biological muscle performance, properties, and control. In doing so, we review advances in understanding of biological muscle properties that contribute to their high adaptability and compare them with some of the newest soft actuation technologies. The reviewed soft actuators with compliances ranging from ∼0.1 to 10 MPa^{-1} that perform contractile or bending actuation are the focus of our study as these are the most common actuation motions found in biological muscles. For example, skeletal muscles develop contractile actuation while octopus tentacles develop bending actuation. Our comparative study shows that most soft actuators have performance metrics that are similar to those of biological muscles. Most soft actuators have tunable material properties (compliance and damping), integrate sensors in their architecture, and potentially feature variable recruitment. However, some muscle properties are still lacking in soft actuators. Remaining challenges include implementing morphological computation and muscle synergy in control strategies, as well as integrating onboard energy and thermoregulation in the actuator architecture.

Many previous reviews have focused on comparing the performance metrics of soft actuators and biological muscles [21, 24–26]. These works have shown that the current soft actuators' metrics differ from one technology to another, but, in general, are similar to those of biological muscles. The performance comparison in these works have also been used for selecting soft actuators for applications, where the goal is to find the actuator with the metrics that best fit a particular application. However, as shown here, metrics (such as those in table 1) are not the only requirements for soft actuators to mimic biological muscles. To perform safe HMI, soft actuators should also focus on featuring other muscle intrinsic properties (such as those in table 2) that are fundamental for fast adaptation under external perturbations and robust control of the actuation system. Some of these properties are adaptive dynamic response, self-sensing, morphological computation, scalability, variable recruitment, onboard energy, and thermoregulation (table 2) [41, 42, 84, 85, 132]. Furthermore, while some actuation technologies may have the capacity for a particular property (e.g. tunable compliance), not all technologies have yet exploited that property through their control strategies. Developing successful control strategies that can optimize actuation while integrating all the exclusive properties of soft actuators is a key factor for implementation, and the reason why this should be a large focus of future research. Those soft actuators that can better match biological muscle properties are closer to what should be considered a suitable candidate for muscle substitute or 'artificial muscle'.

Soft actuators and robots have been used in a wide variety of applications, only some of which would benefit from muscle-like actuation. Yet, the terms biomimetic actuators and artificial muscles have been extensively used in the soft robotics literature. Considering only applications for which a muscle-like response is desirable, particularly for many HMI and wearable applications, it is useful to clarify the meaning of these terms. On one hand, it seems that biomimetic actuators should feature metrics or properties that are intentionally designed to resemble biological muscles. On the other hand, it seems that artificial muscles could go one step beyond in terms of muscle mimicry by featuring some properties of biological muscles (e.g., tunable compliance) that simplify control and enhance adaptability. Artificial muscles should achieve specific metrics (table 1) and properties (table 2) that enable them to perform well as muscle substitutes. Artificial muscles have been previously defined as 'open-loop stable systems that follow the Hill force–velocity curve' [303]. Once again, in addition to their muscle-like actuation response, we reiterate that artificial muscles should focus on including those properties of biological muscles that simplify control strategies and improve adaptability. However, although Hill models successfully predict force in biological muscles under constant length (isometric) or constant load (isotonic) conditions, the force predictions typically have low accuracy at predicting muscle force during *in vivo* movements [3, 49]; thus, using the Hill force–velocity relationship as a criterion for artificial muscles might be misguided. Other features, such as adaptive dynamics, which is a crucial property of biological muscles [41] might be a better criterion for artificial muscles. This review identified several soft actuators that have the potential to sidestep most shortcomings of the current technologies and even outperform biological muscles (tables 1 and 2, figure 3). We propose that these hypothetical 'artificial supermuscles' would inherently feature the properties of biological muscles (table 2) while also outperforming their metrics (table 1), and bypassing their limitations (section 3.5). Artificial supermuscles could motivate more sophisticated HMI or even allow for human-machine interaction and integration (HMII, see figure 1).

The changing view of muscles as tunable materials provides new directions for investigations geared toward emulating the intrinsic properties of biological muscles.

Conventional actuators have made notable advancements in self-contained and wearable robots. Some examples are all-terrain quadrupedal robots [195, 304, 305], humanoid robots [10, 306], and modular prosthetic limbs [307]. However, as the scale of these autonomous robots decreases, conventional actuators cannot be implemented, and highly integrated soft actuators are needed. A high degree of onboard energy sourcing, sensing, and integration in actuator architecture is crucial for simplifying mobile bio-inspired robots. Self-contained robots must be capable of carrying themselves (energy source, body/frame, control system, manipulators, and drivetrain) while still achieving high performance metrics (section 4.1). We suggest that specific performance metrics, such as those in table 1, should include the weight of onboard energy sources and sensors, not just the weight of the actuator for fair comparison with muscles [19, 84].

Control of soft actuators, in particular, could benefit from emulating control of biological muscles, including self-sensing, adaptive dynamic response, morphological computation, and variable recruitment. These properties simplify control compared to conventional robotic systems [227, 228, 230, 231, 233]. However, some concerns remain regarding how to properly design feedback controllers without altering the natural compliance of the robot [232], and how to excite the robot's natural dynamics efficiently [244]. In addition, soft actuators' tunable compliance and damping should be characterized, modeled, and integrated into control strategies for applications. As most soft actuators are viscoelastic, predictive models will require characterizing the viscoelastic behavior of the soft materials, which is more complicated than for elastic materials. Neuro-inspired control models for soft robots appear to be ideal for integrating adaptive dynamics in control strategies, as initial efforts have already been successfully implemented in conventional [11, 190–192, 194] and soft actuators [308–312] and machine learning techniques have been used to continuously improve control [313–315].

In conclusion, future work in the field of soft robotics should focus not only on designing novel actuator technologies with specific performance metrics, but also on developing and deploying inherent properties of biological muscles such as adaptive dynamics. Only then can these actuators be successfully used as substitutes for biological muscles.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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