Polymeric materials as artificial muscles: an overview

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NATURE AS BIOLOGICALLY INSPIRED MODEL FOR ARTIFICIAL MUSCLES

Biological materials exhibit mechanical properties resulting often from their complex hierarchical structures, which span the nanometer up to millimeter length scale. It is now widely accepted that material behavior depends foremost not only on its chemical composition and physical structure but also on scale, this dependence being most evident at the nanometric level. This aspect represents only a partial explanation for the unique mechanical properties of biological materials, often attributed to their nanostructure details and hierarchy. The collaboration between disciplines ranging from engineering to science is the first step in decoding the physics and the mechanics of these systems, and this is mandatory for designing both replacement materials for medical applications and models for new structural materials that mimic biological design for industrial applications (1).

In a framework where nature is leading scientists, biomimesis is the paradigm of the development of new materials and novel technologies through the distillation of principles from the study of biological systems (2). Starting from materials science, architecture and computer science and finally on to robotics, biomimetic technologies arise from a flow of ideas from the biological sciences into engineering, benefiting from the billions of years of design effort performed by natural selection in living systems. The key process is evolution: nature has "experimented" with various solutions to its challenges and has improved the successful ones (3).

Human history is getting behind of a growth order and is based on "only" 2 million years of material science practice, starting from the age of stone, copper, bronze and iron, followed by the Industrial Revolution based on steel and the Information Age based on silicon semiconductors. Among the latter-day wonders are synthetic rubber, celluloid and rayon, continuing on to aluminium

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alloys, plastics and composites (4, 5). Biological materials show capabilities that in some cases surpass those of man-made ones, regarding both structure and material synthesis. Some of nature's solutions and capabilities might inspire new mechanisms, devices and robots (3, 6). There are plenty of prototypes and attempts to create a robot that fully mimics the shapes and performance of biological creatures, such as the human body and the natural muscles that are a highly optimized system.

Muscles are drivers of human and animal movement: they are the biological elastic actuator. A glance at the complexity and variety of the generated movements shows that muscle is a versatile, powerful and flexible actuator (7-9), capable of working in different modes modulating the dynamic of contraction and structural implementation (10). The development of artificial muscles is a challenging topic for a widespread number of applications and in particular in biomedical science for the construction of orthotics and prosthetics for rehabilitation purposes, as well as for minimally invasive surgical and diagnostic tools, and in robotics science for developing human-assistance devices and walking machines (11-13). One of the key aspects of making biologically inspired robots is the development of actuators that allow the emulation of the behavior and performance of real muscles. A muscle-like technology would be an enormous benefit for medical implants.

Muscles are driven by a complex mechanism and are capable of lifting large loads with short response time (milliseconds). The operation of muscles depends on the chemically driven reversible hydrogen-bonding between 2 polymers, actin and myosin. A peak stress of 150-300 kPa is developed at a strain of about 25%, while the maximum power output is 150-225 W/kg. The average power is about 50 W/kg with an energy density of 20-70 J/kg that decreases as speed increases. Although muscles produce linear forces, all motions at joints are rotary. Therefore, the strength of an animal is not just a muscle force, but a muscle force modified by the mechanical advantage of the joint, which usually varies with the joint rotation. Finally, muscles are able to operate for billions of cycles over a period of a hundred years or more, due to the ability to regenerate proteins in situ (14, 15). The desirable properties of the biological muscles are summarized as follows: they are energy efficient, they have a high contraction ratio, they are intrinsically compliant, their stiffness can be varied smoothly and dynamically and they also incorporate a sensory part (12).

It seems clear that the settlement of a proper actuation mechanism for bioinspired robots is a limiting factor. Hence, the key aspect is the development of actuators that can emulate the behavior and performance of real muscles.

Muscles contraction very much resembles the phase transition that occurs in synthetic polymeric systems. The mechanism used to construct artificial muscle contraction is not very different from that for constructing natural muscles: both employ polymer-gel phase transitions. Therefore, it may be possible to construct artificial muscles with greater speed and efficiency by looking more closely at how nature accomplishes the task of the biological contraction. In the last few decades, to emulate the behavior and performance of real muscles, research efforts have been focused on polymers able to change their volume or shape as a consequence of an external stimulus. In particular, the polymer network is able to expand or to shrink on the basis of the balance between repulsive intermolecular forces, due to electrostatic or hydrophobic interactions, and attractive forces, based on hydrogen or van der Waals bonds. The induced volume or shape change can be modulated by modifying parameters such as solvent, gel composition, temperature, pH, light, or through electrical or magnetic stimulus. On the basis of these considerations, the following materials were investigated for actuator applications: chemically activated polymers, shape-memory polymers (SMPs), inflatable structures including McKibben muscle, light activated polymers, magnetically activated polymers, thermally activated gels and electroactive polymers (EAPs) (16).

A common difference between natural and artificial muscle filaments (as well as other biological filaments) is that natural filaments are generally parallel and cross-linked, whereas artificial gels are typically random. The parallel arrangement may be a critical factor for high speed, and also cross-linking may be critical. In the absence of cross-linking, muscle filament polymers will swell, much like the gel. So cross-links keep filaments closely packed and unable to swell appreciably.

Among the several polymeric systems studied for actuator applications, this review is focused on materials based on 2 different approaches: (i) a shape-memory effect (SME), in which after being severely and quasi-plastically distorted, shape-memory materials show the ability to recover their original shape, thus providing that there is an external source of energy (stimulus), (ii) a shape-change effect (SCE), by which a material alters its shape (in elastic or superelastic behavior) in response to the right external stimulus (17). In the following sections, basic principles related to the application of either SME or SCE are discussed and compared from a general perspective.

SHAPE-MEMORY POLYMERS

General properties

Shape-memory materials (SMMs) are a class of fascinating materials that possess the ability to recover considerable – apparently plastic – deformations upon exposure to an appropriate external stimulus. Although the first observations of SMEs were much earlier (18), it was only in the 1960s, when SMM research and development witnessed an upsurge, that the properties of equiatomic nickel-titanium alloys were discovered. Our understanding of shape-memory mechanisms and the ability to control their effects have moved forward at an increasing pace since then, so that SMMs can be now considered to be one of the most promising classes of functional materials for the design of advanced systems (19-22).

SMPs are a class of SMMs gaining increasing attention because they have properties of flexibility, biocompatibility and a wide scope of modifications (23): in some applications, the SME of this class of polymers might overcome those of shape-memory metallic alloys (SMAs); for examples, see some of their advantages as described in Table I.

Moreover, the main reason for this interest is related to the versatility of SMPs based on polymeric systems. Effectively, they can be designed using macromolecular chemistry, to fit the specifications of different applications by tailoring their properties over a wide range of elastic modulus, maximum strain and triggering stimuli. All of these macroscopic properties can be controlled by a specific variation of molecular parameters. This makes it possible to control the specific combination of the properties of SMPs that are required for definite applications, just by a slight variation of the chemical composition (24). This aspect is strongly limited in other classes of materials showing SMEs.

Most frequently, in SMPs, the external stimulus used to trigger the macroscopic recovery shape has been an external temperature gradient. To date, both direct and indirect thermal heating (due to dissipation processes, Joule effect heating, etc.) have been described. Nevertheless, other stimuli are also reported – namely, electromagnetic and chemical (17, 21, 24, 25).

TABLE I - MAIN PROS AND CONS OF SHAPE-MEMORY POLYMERS IN ARTIFICIAL MUSCLE DESIGN

Actuators	Shape-memory polymers
Advantages	Large shape/form change, larger than SMAs Wide range of actuation stimuli Variety of stimuli (chemical, physical) Easy manufacturing processes
Disadvantages	Based on a phase change that is often temperature controlled Mainly double-state No intermediate states Lower stress generating capacity (compared with SMAs) Lower stiffness (compared with SMAs) Lack of intrinsic reversibility

SMA = shape-memory metallic alloy.

A SMP is generally characterized by 2 different macroscopic shapes: (i) a permanent shape, obtained by a conventional manufacturing technology for polymer processing, according to its chemicophysical structure (e.g., extrusion for thermoplastic polymers); and (ii) one (or many) temporary shape, obtained via a quasi-plastic deformation to dimensions fitting the envisaged application (26). This process consists either of heating the sample, deforming and cooling down to a specific temperature, or of drawing the sample at a low temperature. Both of these approaches to imparting the temporary shape from a permanent one are conventionally called programming. SME in SMPs is characterized by the ability of the material to keep virtually forever the quasi-plastic deformation obtained via programming (17) and by a full recovery to the permanent shape when the trigger is activated.

From a physicochemical point of view, SMP systems consist of 2 segments/phases, and they can be considered as copolymers: one of them is a fixed phase (hard segment [HS]) and the other is a reversible or switching one (soft/switching segment [SS]). The fixed phase prevents the free flow of the surrounding polymeric chains upon the application of a stress. The reversible phase undergoes deformation in a shape-memory cycle and is responsible for the SMP's elasticity. This phase acts as a "molecular switch," freezing the deformed shape below the transition temperature or releasing it and recovering the original shape at or above the transition temperature (T_{trans}). The permanent shape is given by either physical or chemical cross-links. On the basis of the nature of their cross-links, SMPs are subdivided into 2 categories: physically cross-linked SMPs and chemically cross-linked SMPs. On the basis of the switching segments, SMPs are subdivided into 2 categories: SMPs with an amorphous switching segment ($T_{trans} = T_g$) and SMPs with a crystalline switching segment ($T_{trans} = T_m$). Thermally activated SMPs are hence characterized by 2 temperatures: (i) a transition temperature, T_{trans}, that triggers the shape-memory effect, and it can be a T_g, T_m or T_{mix} (a combination of 2 differents T_g, in the case of polymer blends); and (ii) T_{perm}, which represents the upper limit in temperature for maintaining the permanent shape, and which can be a T_m for thermoplastics or the decomposition temperature in the case of thermosetting polymers. When a polymer is in its temporary shape, the permanent shape is stored until the material is heated to above the T_{trans}. Further cooling down the polymer below the transition temperature leads to any recovery of the temporary shape: the effect described is referred to as a 1-way shape-memory effect (1W-SME) (27). By further programming, including mechanical deformation, the work piece can be brought into a temporary shape again by an external application of a deformation: this new temporary shape does not necessarily match the first temporary shape (28).

Moreover, in several SMPs, this recovery has been reported to be stable for several cycles (26, 29, 30).

Opposite to 1-way SME, where the permanent shape is defined in the manufacturing process and different temporary shapes are possible by programming, 2- and 3-way effects are also reported. Two-way SMMs are capable of switching between 2 geometries provided by an exposition to an external cycle. Similarly, triple SMMs are capable of fixing 2 temporary shapes that are recovered before the permanent shape is reached. Generally, this n-way of SMMs are multiphase polymer networks containing at least 2 separated domains, each associated with a specific transition temperature (26, 29, 30).

Along with development of new materials exhibiting SME, different representative models have been introduced, ranging from very general to material-specific, as well as from very simple to extremely complex.

Reported mechanisms for thermally activated SME in polymers are essentially 3:

1. Dual-state mechanism: the temperature increase promotes a glass to rubber transition of state in the polymer matrix, and it is an entropy-governed process. Hence, using T_g, all elastomers are naturally SMP (17). However, both cross-linking and T_{trans} in a range that is relevant for a particular application are required to ensure high shape recovery ratios (27) and the SME mechanism to be activated (23).
2. Dual-component mechanism: temperature increase promotes a phase transition in 1 of the components that is dispersed in a highly elastic matrix. In this case, the matrix shows a highly elastic behavior within the working range, and the transition segment shows a reversible stiffness change at a defined interval. This class of SMP includes dual-segmented structures or, more generally, a 2-segment/2-domain structure, such as is the case for polyurethanes, which have been widely investigated due to their versatile modification properties (22, 23, 26, 29, 30). To date, the reported T_{trans} are both T_g and T_m, according to the transition temperature of the trigger phase.
3. Partial-transition mechanism (PTM): this has recently been proposed by Huang et al (17) to explain the behavior of some polymers in which an additional contribution to the recovery is from the hard part of the transition component, which does not undergo the transition during programming.

Among the possible models, the "switches and net points" (31) is a simple model that well fits for a large number of polymers and triggering stimuli: polymer networks consist of net points (chemical or physical bonds) determining which switches are responsible for strain fixation and partial strain recovery. In thermally induced SMP, switches are often represented by a low T_g amorphous or low T_m semicrystalline phase.

It is increasingly evident that such definitions and classifications encompass all polymers, and it is debatable whether SME is an intrinsic polymer property. Huang et al (17) suggest that thermo- and chemo-responsive SMEs are intrinsic features of most polymers, just like density and specific heat are of all polymers. Despite this debate (27), it is evident that tailoring the material properties and characteristics of SMPs to meet specific requirements of targeted applications is an essential aspect of the development of new polymers, as we discuss further in the next section.

Design of SMPs for actuation systems

Shape-memory behavior can be observed for several polymers that may differ significantly in their chemical composition. SME, in fact, is not related to a specific material property of a single polymer; it is the result of a combination of polymer structure and morphology together with the applied processing and programming technology (26). Lendlein and Kelch first published (26) a very complete overview of the chemicophysical properties of different SMPs and their transition temperatures, which has been further extended by other authors, sometimes addressing specific application fields (21, 28-31). In general, SMPs exhibit low strength and stiffness, and this limits their use for many advanced applications. The efficiency of the SME is controlled by the composition of the polymer, in terms of chemical structure, molecular weight, degree of cross-linking and fraction of amorphous and crystalline domains. As previously discussed, some properties should be specifically addressed when designing actuators.

The low stiffness produces only a small recovery force in the temperature change process. Hence, blending and interpenetrating polymeric networks have been investigated. On the other hand, the incorporation of reinforcing fillers has been evaluated too, to improve the mechanical properties and shape recovery stress and to diversify the applications of SMPs. In this way, the external heating used to stimulate conventional SMPs, which is critical for many applications (such as body actuators) (32), can be avoided: thus use of electric triggering of SMP composites could enlarge their technological potential.

SMPs composites, which act to improve a certain function as multifunctional materials or the mechanical properties as structural materials, can be fabricated with specific types of conductive fillers (33, 34). The properties of the final composite products are significantly affected by many factors such as processing techniques, filler distribution, interface, filler size, aspect ratio and matrix nature. Some examples of fillers are carbon black, carbon nanotubes, carbon nanofibers, Ni chains, electromagnetic fillers, microfibers, fabrics, nanoclays, SiC nanostructures and other inorganics. Natural muscles can be counted among nature's engineering masterpieces, as they are in fact efficient, powerful, rapid and finely controllable actuators. Therefore it is easy to understand the reason biomimetic motion is considered highly desirable. Artificial muscles could outperform traditional electromechanical actuators in a number of industrial fields by providing considerable force in an extended range of motion, while being lightweight and compact. Furthermore, a muscle-like technology would be of enormous benefit for biomedical applications, such as human-assistance devices or minimally invasive surgical equipment. However, for artificial actuator technology to become an established alternative to currently employed mechatronic systems, some technological issues still need to be addressed, particularly in terms of controlling mechanisms, supplied power and range of motion. The recent research advances in the field of SMPs offer an extraordinary opportunity to develop new solutions with this remit, and accordingly, significant research efforts are being turned toward the use of SMPs in the development of biologically inspired actuators.

Compared with other smart materials (i.e., piezoelectric, SMA), SMPs are (i) low cost (one twentieth the cost of SMAs); (ii) lightweight (one seventh that of SMAs); (iii) rigid in the low temperature range and flexible in the high temperature range; (iv) characterized by high strains, greater than 400% (7% maximum in SMAs); and (v) easy to process for creation of complex 3D shapes.

Examples of applications of SMPs as actuators in artificial muscles

The use of SMPs has been proposed to design an improved version of one of the first devices intended as an approximation of biological muscles, the McKibben pneumatic actuator. The traditional layout of McKibben actuators consists of an air bladder surrounded by a mesh shell made with very low extendable material: when the bladder is inflated with air, the bulging of the bladder draws in the end of the shell, providing actuation by generation of an axial force. One limitation of this type of actuator is represented by the unsuitability of maintaining the actuated state easily and with low or no energy consumption. To overcome this major limitation, Takashima and colleagues (35) have experimented with the impregnation of actuator mesh with a 45°C T_g–activated SMP, thereby introducing temperature as an additional variable to control the actuator. The bladder can in fact be inflated and deflated at $T>T_g$, but when the system is cooled down, the actuated state is firmly maintained by the shell itself in a glassy state, with no need for additional pressurization. Thanks to the introduction of SMP, this new version of McKibben artificial muscle not only allows us to firmly freeze different activated states but also to differentially control actuation by pressurizing at $T<T_g$ and activating contraction with temperature or any other SMP-triggering stimulus.

Despite the brilliance of this simple but effective solution, it is clear that 1-way SMMs serviceable in the development of innovative actuators are limited by the fact that a different source is required to complete the actuation cycle. One possible solution to realize an actuator entirely based on SME using a 1-way SMP was recently proposed for the design of Micro Electro-Mechanical Systems (MEMS) actuators (36). The actuators rely on 2 different SMPs with separate glass transition temperatures (T_{g1} and T_{g2}, with $T_{g1}<T_{g2}$) and opposite effects of the 2 transitions. The shape effect caused by overcoming T_{g2} overturns the previous memory shape obtained in raising the temperature over T_{g1}.

Compared with 1-way SMPs, 2- or multiple-shape-memory polymers are more likely to be developed into effective and smart actuators that can operate only by cycling temperature or the triggering stimuli.

ELECTROACTIVE POLYMERS

General properties

Electroactive polymers (EAPs) are exciting new smart materials with many anthropomorphic characteristics, and hence an emerging class of actuation materials. They represent an attractive alternative to motors and conventional materials. As a matter of fact, these polymers have functional similarities to biological muscles including resilience, damage tolerance and large actuation strain (stretching, contracting and bending). Moreover, EAP materials can be used to make biomimetic devices that otherwise may have been impossible to engineer and considered nothing more than science fiction. So, they are actuators that most closely emulate human muscles, and therefore they have earned the moniker "artificial muscles."

Initially, EAPs received relatively little attention because of their limited actuation capability. In the last 15 years, a series of EAP materials have emerged that exhibit a significant shape change in response to electrical stimulation. The impressive advances in improving their actuation strain capability are attracting the attention of engineers and scientists from many different disciplines (37).

EAPs benefit from many of the appealing characteristics of polymers: they are lightweight, inexpensive, fracture tolerant, pliable and easy to process in various shapes. They can potentially be integrated with sensors to produce smart actuators. The capability to produce EAPs in various shapes and configurations can be exploited using such methods as stereolithography and ink-jet processing techniques.

Based on their activation mechanism, EAP materials can be divided into 2 major groups: electronic EAPs and ionic EAPs. The former, classified also as dry EAPs, are driven by coulomb forces and include dielectric elastomers and electrostrictive polymers, dielectric or ferroelectric polymers. The latter, electrostrictive polymers involve a transport of ions/molecules in response to an external electric field (usually these materials contain an electrolyte) and consist of 2 electrodes and an electrolyte. Ionic EAPs, known also as wet EAPs, comprise ion polymer metal composites (IPMC), conducting polymers (CPs), carbon nanotubes (CNTs) and electroactive gels.

Each EAP category presents a specific electromechanical behavior, so that this class is able to satisfy the requirements of different applications (38).

Generally, electronic EAPs can operate in room temperature conditions for a long time, respond at very high frequencies and hold strain under DC activation (Fig. 1). As regards their performance, they are characterized by large actuation forces, low response time (millisecond level), high efficiency, high stability, high reliability and high durability. The basic mechanism implies high driving voltages (~150 V µm^{-1}); in addition, these materials present a glass transition inadequate for low-temperature actuation tasks, and require a compromise between strain and stress.

On the other hand, ionic EAPs can be activated by very low voltages (on the order of 1 V) and show large bending displacements (Fig. 2). Notwithstanding this, it is important to underline the fact that in aqueous systems, they suffer electrolysis at >1.23 V, and in air, they require specific electrolytes. In addition, ionic EAPs present low responses (fraction of second), do not hold strain under DC voltage (except for CPs and CNTs), operate at low frequencies (several Hertz) (39).

Design of EAPs for actuation systems

Generally, the main properties that are expected to be of most significance in assessing the capability of EAPs as potential actuators include electrically induced stress (MPa) and strain (%), operation bandwidth (Hz) or response time and relaxation; required driving voltage (V); power density (W cm^{-3}); efficiency (%); lifetime (cycle); material density (g cm^{-3}) as well as environmental constraints and behavior (37). The data related to several EAPs – dielectric elastomers (40-42), piezoelectric polymers (43), conducting polymers (44-46), carbon nanotubes (46-48) and polymer metal composites (49, 50) – are compared with those of SMPs (51) in Table II.

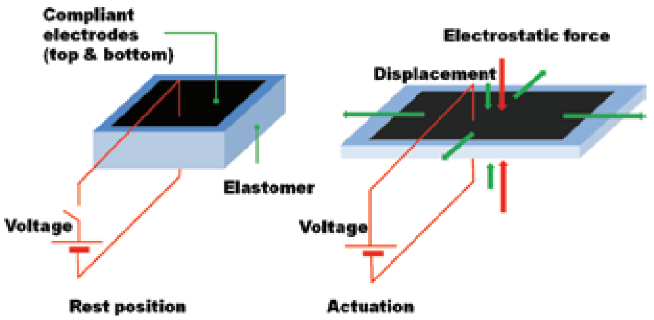

Fig. 1 - *Electronic electroactive polymers (EAPs) driven by the electric field or coulomb forces: this implies the use of high driving voltages.*

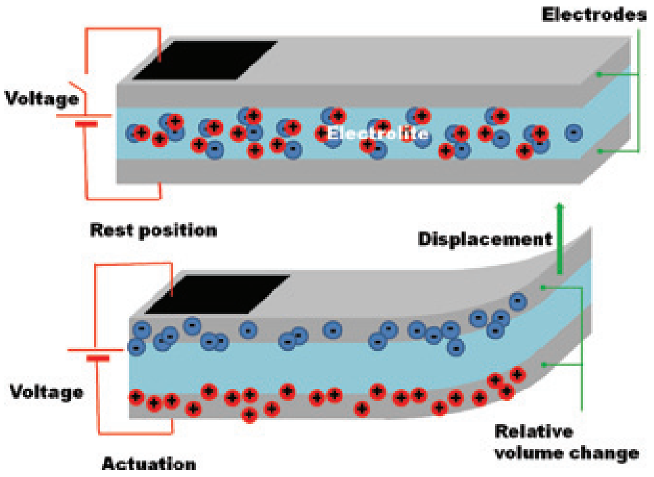

Fig. 2 - *Ionic electroactive polymers (EAPs) contain an electrolyte, and transport of ions/molecules in response to an external electric field is involved: this transport results in an internal stress distribution that leads to volume expansion/contraction to bending.*

Even if the induced displacement of both the electronic and ionic EAPs can be designed geometrically to bend, stretch or contract, it is necessary to underline the fact that ionic EAPs provide mostly bending actuation (longitudinal mechanism can be articulated), inducing a very low actuation force. Moreover, for these materials, natural bidirectional actuation depends on the polarity voltage (39).

Examples of applications of EAPs as actuators

Providing a complete overview of the future possibilities for EAP technology is a tall order, as novel mechanisms, biologically inspired, are always around the corner, and EAP materials can potentially provide actuation with lifelike response.

Using these materials as actuators, various novel mechanisms and devices have already been demonstrated, including a robot fish, catheter-steering element, miniature gripper, loudspeaker, active diaphragm, dust wiper and artificial muscles for robotic arms – as briefly described in the following. A bistable electroactive

TABLE II - MAIN CHARACTERISTICS OF ELECTROACTIVE POLYMERS (EAPs) AND SHAPE-MEMORY POLYMERS (SMPs)

	Dielectric elastomers [%]	Piezoelectric polymers	Conducting polymers	Carbon nanotubes	Polymer metal composites	SMP
Typical (max) strain	25 (>300)	0.1	2 (40)	0.2 (1)	0.5 (3.3)	100
Typical (max) stress [MPa]	1.0 (7.0)	4.8	5 (200)	1 (27)	3 (15)	4
Typical (max) specific elastic energy density [J/g]	0.1 (3.4)	0.0013	0.1 (1.0)	0.0087 (0.04)	(0.004)	2
Typical (max) elastic energy density [J/cm3]	0.1 (3.4)	0.0024	0.1 (1.0)	0.002 (0.04)	(0.006)	2
Typical (max) avg. specific power density at 1 Hx [W/g]	0.1 (3.4)	0.0013	0.1 (1.0)	0.01 (0.270)	0.004	<0.2
Peak strain rate [%/s]	>450	NA	1	0.16	3.3	NA
Elastic modulus [MPa]	0.1-10	450	200-3,000	10,000	50-100	NA
Est. max. efficiency [%]	60-90	60-90	<5	0.1	1.5-3	<10
Relative speed (full cycle)	Medium-fast	Fast	Medium-Slow	Fast	Medium - Slow	Slow

polymer has been applied as actuator for a refreshable Braille display device (52) or to fill a real-time sensory feedback device (Biomimetics Laboratory, New Zealand). ViviTouch is now applying EAP technology in a brand new way to the portable headphone category (ViviTouch®, USA). A small, lightweight EAP-based variable-stiffness mechanism has been demonstrated to alter the leg compliance of the high-speed, autonomous, hexapedal robot iSprawl (Florida State University, College of Engineering). Moreover, artificial muscles have been developed to provide fast torsional and tensile actuation (53): these muscles can spin a rotor at an average of 11,500 revolutions/min and provide up to 27.9 kW/kg of mechanical power density during muscle contraction. Taking advantage of the features of a polymer actuator, a super small optical image stabilizer device has been developed (Eamex Corp., Japan).

These successful applications have demonstrated the feasibility of the exploitation of EAPs for actuator development, but further improvements in power and robustness will be necessary.

Notwithstanding this, today the EAP field is approaching the first transition from research to industrialization, with large companies starting to invest in this technology, first in Japan and United States, and now also in Europe.

CONCLUSIONS

Nowadays, traditional actuators require mechanisms containing gears, bearings and other complex components that are expensive and prone to failure. Substitution with materials that emulate biological muscles can enable novel manipulation capabilities not achievable with the manmade technology. Polymeric materials are elastic and fracture tolerant, and can be used to make noiseless actuators that can be easily shaped, miniaturized and made low-energy consuming.

However, other improvements are required: implementation of standard tests to allow comparisons between different materials, performance classifications and construction of databases; ensuring robustness and performance repeatability to produce reliable materials; and hard work on actuator design that helps to overcome the defects of the single materials and to improve their properties.

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