Dielectric Elastomer Artificial Muscle Actuators: Toward Biomimetic Motion

Ron Pelrine, Roy Kornbluh, Qibing Pei, Scott Stanford, Seajin Oh, Joe Eckerle
SRI International

Robert Full, Marcus Rosenthal
University of California at Berkeley

Kenneth Meijer
Technical University of Eindhoven, The Netherlands

ABSTRACT

To achieve desirable biomimetic motion, actuators must be able to reproduce the important features of natural muscle such as power, stress, strain, speed of response, efficiency, and controllability. It is a mistake, however, to consider muscle as only an energy output device. Muscle is multifunctional. In locomotion, muscle often acts as an energy absorber, variable-stiffness suspension element, or position sensor, for example. Electroactive polymer technologies based on the electric-field-induced deformation of polymer dielectrics with compliant electrodes are particularly promising because they have demonstrated high strains and energy densities. Testing with experimental biological techniques and apparatus has confirmed that these “dielectric elastomer” artificial muscles can indeed reproduce several of the important characteristics of natural muscle. Several different artificial muscle actuator configurations have been tested, including flat actuators and tubular rolls. Rolls have been shown to act as structural elements and to incorporate position sensing. Biomimetic robot applications have been explored that exploit the muscle-like capabilities of the dielectric elastomer actuators, including serpentine manipulators, insect-like flapping-wing mechanisms, and insect-like walking robots.

Keywords: biomimetic, artificial muscle, electroctive polymers, dielectric elastomers, robots, walking

1. INTRODUCTION

It has long been a goal of roboticists to achieve lifelike motion. This goal is perhaps partly motivated by anthropomorphism, yet there are powerful technical motivations to developing lifelike robots. The entertainment industry, with its need for humanoid robots and robotic creatures, is one major application area that can benefit from lifelike robots. Beyond mimicking the appearance of natural organisms, there are a number of strong performance motivations for achieving lifelike performance, as opposed to lifelike appearance. Natural creatures put man-made robots and devices to shame when it comes to navigation of obstacles, speed over rough terrain, agility, and, in many cases, power or energy output per unit weight in accomplishing certain tasks.

One immediate, and probably the most significant, obstacle in achieving lifelike appearance or performance is the lack of a commercial actuator technology that can truly mimic natural muscle even at its most basic performance. Table 1 shows a qualitative comparison between natural muscle and various commercial actuator technologies. If we look closely at quantitative performance, we find that although natural muscle is not the best in many individual categories of performance, it is good in virtually all measures of performance. This leads to the observation that conventional technologies fail to achieve lifelike motion not because they cannot match or exceed natural muscle performance in any given performance measure, but rather they fall short because they do not equal natural muscle in *overall* performance.

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Table 1. Comparison of natural muscle and man-made actuator technologies (note: electromagnetic and magnetostrictive technologies are efficient at high speeds, but inefficient at low speeds–hence their poor speed rating).

Actuator	Strain	Actuation Pressure	Density	Efficiency	Speed (fast AND slow)
Natural Muscle	●	●	●	●	●
Electromagnetic	●	●	○	●	○
Piezoelectric	○	●	◐	●	●
Shape Memory Alloy	◐	●	◐	○	○
Magnetostrictive	○	●	○	●	○
Electrostatic	●	○	●	●	●
Dielectric Elastomers	●	●	●	●	●

○ = Poor ◐ = Fair ● = Good

One observation from Table 1 is that electrostatic actuators meet all the performance requirements of an *artificial muscle* except in actuation stress. Whether one views dielectric elastomer (DE) technology as a way to increase actuation stress in electrostatic actuators, or as a muscle-like actuator technology in its own right, Table 1 shows that, like natural muscle, dielectric elastomers can also achieve good overall performance. But how muscle-like are dielectric elastomer actuators? To answer this question we must consider factors beyond stress-strain, or indeed beyond those listed in Table 1. Research into natural muscle shows that muscle has a number of other important properties such as damping, elasticity, braking functions (actively absorbing mechanical energy beyond simple damping), and even integrated sensing [Dickinson et al., 2000]. While probably not all these functions are needed simultaneously to achieve lifelike motion and/or performance in many cases, the biomimetic actuator designer must consider the range of natural muscle capabilities and how they relate to the capabilities of a given actuator technology.

This paper looks more closely at the comparison between natural muscle and dielectric elastomer technology. After considering the basic principles of dielectric elastomer actuators, we compare the properties of natural muscle with this technology and show how it is similar and how it is different. The significance of the similarities and differences between dielectric elastomers and natural muscle in the quest for truly biomimetic robots is discussed. Following this discussion, we describe the present state of the art in dielectric-elastomer-powered robots and how future work should lead to potentially remarkable biomimetic systems.

2. DIELECTRIC ELASTOMER ACTUATORS

Figure 1 shows the principle of operation of dielectric elastomers. A polymer is sandwiched between two compliant electrodes [Pelrine et al., 1998]. A voltage difference is applied between the compliant electrodes, causing compression in thickness and stretching in area of the polymer film. The term “dielectric elastomer” is commonly used because most polymers used with this approach are elastomers. However, very good performance has also been achieved with polymers that are not elastomers (i.e., polymers that cannot elastically strain 100%).

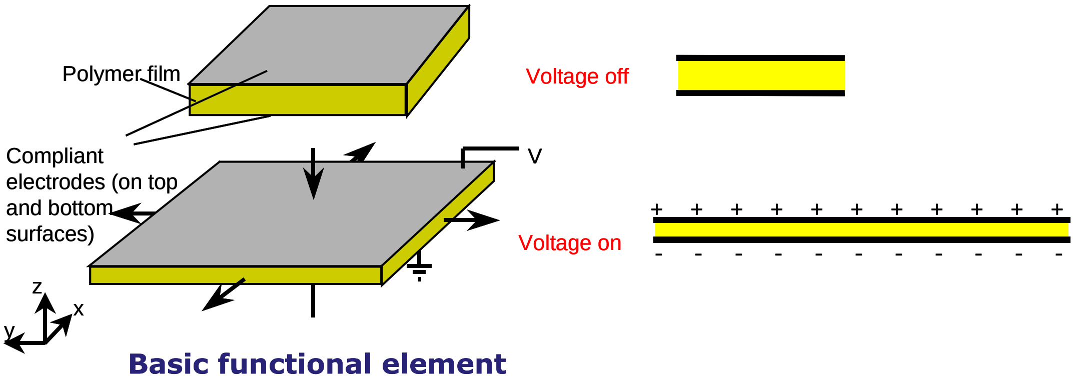

Figure 1. Principle of operation.

The simplicity of operation of the dielectric elastomers hides a number of subtle features. We noted earlier that dielectric elastomers can be thought of as a way to increase actuation stress in an electrostatic-based actuator. The advantages in actuation stress over a conventional air-gap or vacuum electrostatic actuator are not immediately apparent from Figure 1, but closer examination reveals the differences. First, note that in a dielectric elastomer the electrodes expand in area in addition to coming closer together as the film thickness decreases. Coming closer together converts electrical to mechanical energy by bringing opposite charges closer. This mode of energy conversion is present in air-gap electrostatic actuators that use rigid electrode plates. However, dielectric elastomers convert electrical to mechanical energy by expanding in area, a mode not present in conventional air-gap actuators. The stretching mode also converts electrical to mechanical energy, a phenomenon most easily seen by noting that stretching separates like charges and hence reduces electrical energy (or, equivalently, increases capacitance that reduces electrical energy at fixed charge). The reduction in electrical energy is balanced by an increase in elastic mechanical energy and/or mechanical work output. Thus, dielectric elastomers have two modes of conversion of electric to mechanical energy, compared to one mode for conventional air-gap electrostatic actuators. The two modes of conversion are directly coupled in dielectric elastomers because elastomers can change shape only by maintaining a substantially constant volume (i.e., stretching in area is mechanically coupled to contraction in thickness and vice versa). Thus, it makes sense to speak of a single effective actuation stress or pressure in dielectric elastomers [Pelrine et al., 2000; see also Kofod et al., 2001], and the actuation pressure, *p*, for dielectric elastomers can be written as

$$p = \varepsilon\, \varepsilon_o\, E^2 = \varepsilon\, \varepsilon_o\, (V/t)^2 \qquad [1]$$

where ε_o is the permittivity of free space, ε is the dielectric constant of the material, *E* is the imposed electric field, *V* is the applied voltage, and t is the polymer thickness. The fact that dielectric elastomers employ two modes of motion compared to one for conventional air-gap electrostatic actuators shows up explicitly in Equation 1. The corresponding actuation pressure for air-gap actuators is one-half the value given by Equation 1.

It is not just in this factor of 2 that dielectric elastomers increase actuation pressure, however. Note that the dielectric constant for air is 1, while most common polymers have dielectric constants roughly in the range 3-10, thus increasing the actuation pressure by an additional factor of 3-10. Last, we note that a number of polymers can be driven to higher electric fields, *E*, than is typically feasible with air- or vacuum-gap electrostatic actuators. The net effect is to increase the actuation pressure in dielectric elastomers typically by a factor of 10-100, and sometimes higher, compared to conventional electrostatic actuators.

Actuation pressure is given by Equation 1, but strain performance of dielectric elastomers is not as easily expressed. The strain exhibited by a dielectric elastomer depends on its modulus, boundary conditions, and external loading. For small strains (e.g., <10%) under free boundary conditions, the thickness strain, s_z, can be written as

$$s_z = -p/Y = -\,\varepsilon\, \varepsilon_o\, V^2/(Y\, t^2) \qquad [2]$$

where *Y* is the modulus of elasticity of the polymer-electrode composite film. We also have the constant volume approximation for elastomers that can be written as

$$(1 + s_x)\,(1 + s_y)\,(1 + s_z) = 1 \qquad [3]$$

where s_x and s_y are the strains in the planar directions of the film. Under isotropic conditions, Equation 3 can be used with s_z to determine $s_x = s_y$, but in general more complex finite element methods must be used.

Dielectric elastomers can be configured in many different ways, and this is a strength of the technology. Various DE actuators have been built and demonstrated. These include rolled actuators, actuators based on stretched films on rigid frames, bimorph and unimorph actuators, diaphragms, and bowtie actuators (so called because the top and bottom rigid end pieces, together with the flexible sides that come in at an angle, make the shape of a bowtie) [Kornbluh et al., 2001]. As with other field-actuated materials, dielectric elastomers can be efficient and fast [Kornbluh et al., 2000].

For biomimetics, certain types of actuator are more appropriate than others, depending on the application. Actuators designed for facial movements or eye dilation will most likely employ designs that are different from those for than leg actuators, for example, even though both may be based on dielectric elastomers.

Although the range of actuators and where they best apply varies depending on the biomimetic goals, several general observations can be made about the various types of actuator and where they are best suited. For example, leg and arm actuators generally require substantial mechanical output from relatively small and compact actuators. These requirements are generally best met with compact multilayer configurations such as rolled actuators. By contrast, achieving lifelike appearance in areas that do not require much force (e.g., eye dilation or certain facial movements) can be addressed with single-layer devices such as framed actuators. Still another area would be biomimetic pump-like actuation such as in an artificial heart or air pump. In this case, a diaphragm actuator or other type that couples well to fluids may be the preferred choice.

3. COMPARISON OF DE ACTUATORS TO NATURAL MUSCLE

In considering the question of how muscle-like dielectric elastomers really are, a number of comparisons can be made [see Full and Meijer, 2000 and Full and Meijer, 2001 for more detailed comparisons], and Figure 2 shows one of the most basic. In this figure, the actuated strain and actuation pressure (normalized by mass density) are shown for various high-speed technologies along with natural muscle. Note that the scale is logarithmic, so while the commercial technologies may appear close to natural muscle on the graph, in practical terms these mature technologies are far from achieving muscle-like performance. As is apparent from the figure, dielectric elastomers cover the strain-actuation pressure range of natural muscle, unlike other existing commercial technologies.

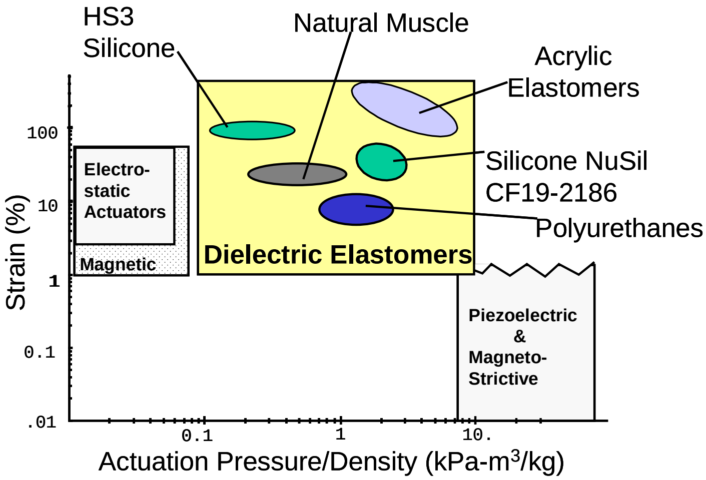

Figure 2. Strain versus actuation pressure/density for various high-speed technologies.

Figure 2 shows rough strain-stress performance, but more detailed measurements are needed for a better comparison. In particular it is important that an actuator technology be able to deliver muscle-like performance at common muscle frequencies. Figure 3 shows a more specific test of natural muscle at various frequencies and a test of an acrylic dielectric elastomer. As can be seen from the figure, the DE actuator fell within the general trend of muscle-like performance.

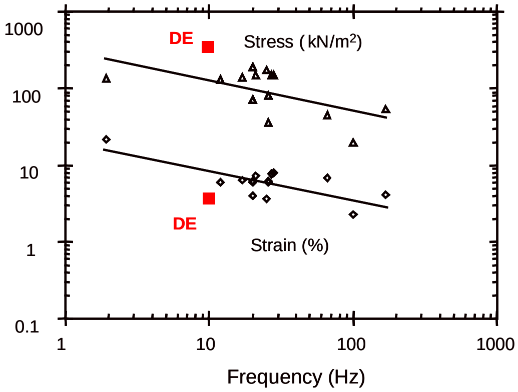

Figure 3. Strain and stress of DE actuator compared to various natural muscle data points [source: Full and Meijer, 2001].

Figure 4 compares power density and work-per-cycle performance. As with Figure 3, the measured performance of the relevant parameter falls within the general trend of natural muscle.

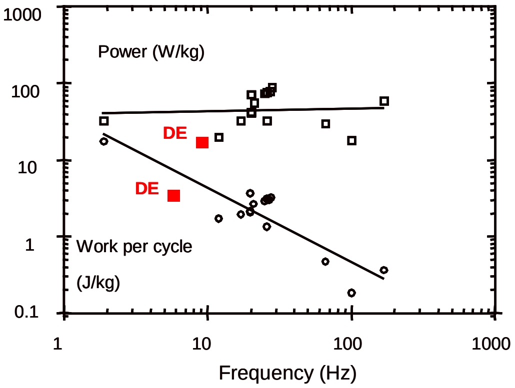

Figure 4. Power density and work per cycle for DE actuator compared to natural muscle data points [source: Full and Meijer, 2001].

We note that Figures 3 and 4 compare a single dielectric elastomer, acrylic, in a single configuration to natural muscle. The experiments also were performed using muscle driving circuits with poor high-frequency performance. Thus, they should by no means be regarded as representative of the ultimate potential of DE actuators, and indeed other tests have shown much higher performance of acrylic. Nonetheless, these figures compare a DE material with various natural muscles under identical strain, stress, and power measurement conditions, and they illustrate that, at least with regard to these parameters, dielectric elastomer technology can achieve muscle-like properties.

It was mentioned earlier that natural muscle has a number of functions besides conventional actuation. In particular, natural muscle has important passive properties that help organisms achieve such remarkable dynamic performance in the presence of obstacles and unexpected perturbations. These properties are thought to be critically dependent on the passive elasticity and damping of the muscle [see, for example, Alexander, 1998]. Figure 5 illustrates the elasticity comparison. This figure shows that silicone DE material (NuSil CF19-2186) has suitable elasticity compared to the cockroach muscle, while acrylic (3M Corporation's VHB 4910) is somewhat stiffer, particularly over the lower range of frequencies.

Figure 6 shows the damping comparison for the same materials and the same cockroach muscle. This graph shows that both acrylic and silicone DE materials have significantly lower damping than the natural muscle. While the damping is not a good match to the natural muscle, particularly for the DE silicone, a lower damping is not expected to be a significant obstacle to achieving biomimetic performance in the long term. This is so because it is relatively easy to increase polymer damping by a number of means, such as by laminating a layer of passive, low modulus, but highly viscoelastic, polymer in the DE film structure. Alternatively, damping may be increased by using advanced electronic techniques for controlling the motion. By comparison, *decreasing* DE damping would have been more challenging since it is often difficult to reduce damping below a certain level for many polymers. However, the need to increase damping to better match natural muscle characteristics may become more important as biomimetic robots are built for high-speed, rough-terrain navigation.

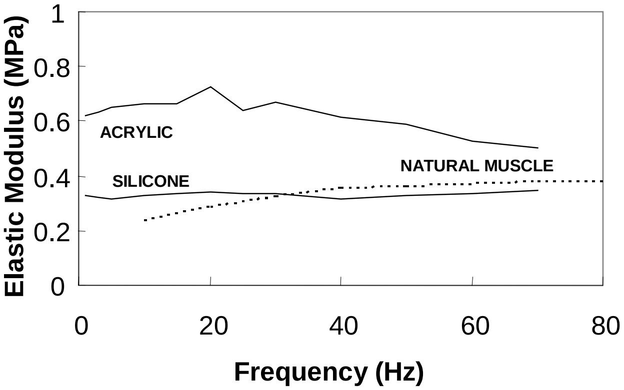

Figure 5. Comparison of elastic modulus for natural muscle and two DE materials.

Other functions of natural muscle are known, but fewer quantitative comparisons to DE materials exist. Natural muscle is sometimes used by certain organisms for braking functions; that is, the muscle is stimulated to push against the existing direction of motion. Such a capability should be feasible with dielectric elastomer materials, and generator modes of operation have been demonstrated using DE technology. Similarly, natural muscle can include integrated sensing and structural functions. DE actuators have also shown similar capabilities as sensors and structural members [Pei et al., 2002]. Quantitative comparisons are mostly lacking in these other areas. However, we note that these other muscle functions are not always used by organisms. Thus, they may not be needed for specific biomimetic robot applications.

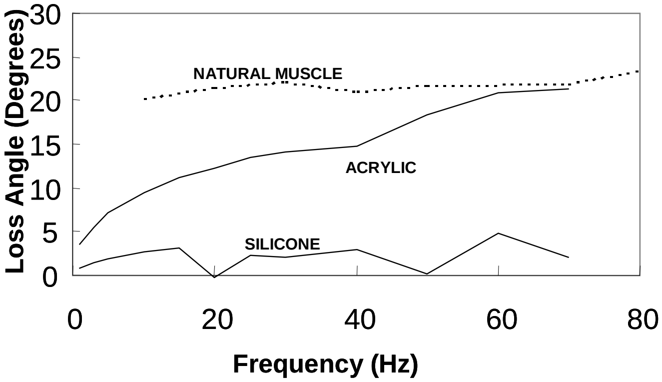

Figure 6. Comparison of the loss tangent (damping) of natural muscle and two DE materials.

Last, we mention one obvious difference between dielectric elastomers and natural muscle: when natural muscles are stimulated they contract, whereas DE films expand when stimulated. For most applications this is not a major issue, although it often influences the choice of specific designs. Many biomimetic applications are primarily concerned with cyclic motions, such as leg motions during walking or continuous cycling of an artificial heart at different frequencies. For cyclic motions, there is usually little difference between an actuator that contracts and one that expands. They have different power-off states, but since the focus is on continuous cyclic motion, that is not a major consideration. Where the difference in power-off states may matter, however, is in noncyclic applications where power or lifetime is a critical concern. For example, if one envisions an application where an eye pupil is expanded

95% of the time and needs to contract only 5% of the time, then a technology that expands when stimulated needs to maintain the stimulation for 95% of the time in the most direct design. In the case of DE materials, this means the DE film must have voltage applied for 95% of the time, which may adversely impact power consumption and/or lifetime. Even in this case, however, the issue is not generally as significant as it might first appear because it can be addressed by building in a suitable margin for the power-on lifetime, and DE materials, being electrostatic in nature, generally consume almost no power even with an applied voltage. Alternatively, often a simple design change can use the expansion of DE materials to make another part of the actuator contract during stimulation.

4. DIELECTRIC ELASTOMER BIOMIMETIC ROBOTICS

In considering how DE technology has been applied to biomimetic robots and how it may be applied in the future, it is important to note that dielectric elastomer actuators do not automatically lead to biomimetic robots. Indeed, dielectric elastomers have been used to make rotary motors and it is feasible, and possibly even advantageous, to replace traditional electromagnetic motors with dielectric elastomer motors in conventional robots. But such designs are not likely to be considered “biomimetic”. Thus, the use of dielectric elastomers, even under the assumption of using a dielectric elastomer that is a perfect analogue of natural muscle, does not guarantee a biomimetic robot, even though it may still be a useful robot in other respects.

One feature common to biomimetic robot design for locomotion is that virtually all designs use direct-drive approaches. Gears and other complex transmissions do not exist in nature, and macroscopic organisms generally have a 1:1 correspondence between their natural muscle motion and motion of a corresponding locomotion appendage (e.g., leg, wing). This does not mean that creatures do not use transmissions in the sense of mechanical leverage such as bones to produce a different stroke-force combination than is supplied directly by the muscle, but appendages generally operate at the same frequency as their corresponding muscles. By contrast, most electromagnetic devices (by far the most common electrical actuators for robots today) cannot supply sufficient energy in a single stroke to be attractive in direct-drive mobile robots, so various means such as gear boxes are employed so that the electromagnetic device can actuate (e.g., for motors, rotate) many times per single cycle of a leg or other appendage. Consistent with this observation is that biomimetic designs are generally back-drivable. That is, pushing on a biomimetic leg, for example, will cause the dielectric elastomer to stretch or contract, and the leg compliance and damping is directly related to the compliance and damping of the DE actuator. By contrast, nonbiomimetic designs often use motors with high gear ratio transmissions, and these are typically not back-drivable. A leg attached to a gear box with a high-gear-ratio will typically be rigid relative to external forces because of the mechanics and friction of the gear box. One can, of course, try to alleviate this difficulty by providing compliance and damping on the leg but external to the motor-gear box combination, but in this case the complexity of the device becomes a significant issue since each leg usually has 2 or more degrees of freedom and there are multiple legs.

Dielectric elastomer biomimetic robots are in their infancy, but already there are encouraging devices that demonstrate the approach. The first DE actuator-driven legged robot, named FLEX 1, is shown in Figure 7 [Eckerle et al., 2000]. FLEX 1 is believed to be the world’s first polymer actuator-driven, autonomous legged robot based on the available literature. FLEX 1 was a battery-powered device that included voltage conversion and microprocessor controller on board. It used dielectric elastomer acrylic bowtie actuators, with two degrees of freedom per leg (up/down and forward/back). FLEX 1 also incorporated biomimetic features, primarily related to the direct-drive design and the use of compliant, viscoelastic polymer actuators. It was driven by a tripod, simple multilegged insect gait.

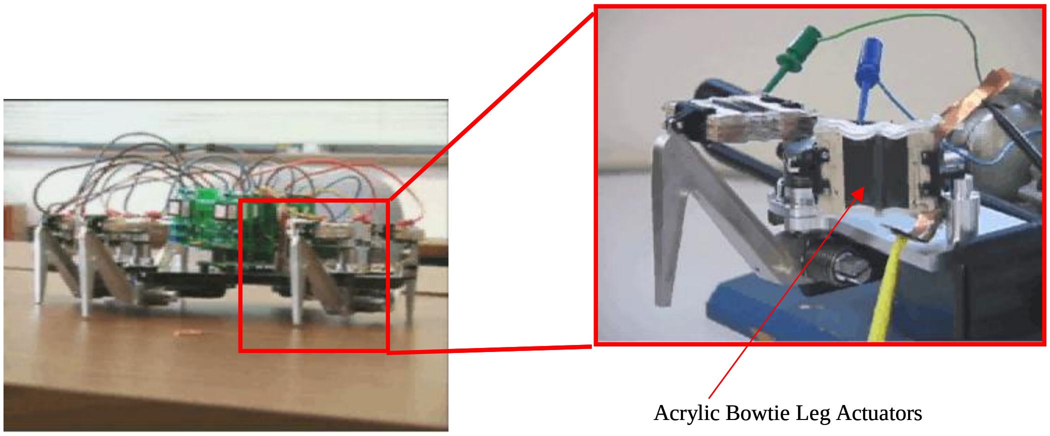

Figure 7. FLEX 1, an autonomous, dielectric elastomer legged robot.

FLEX 1 was a milestone in the field but it was too slow (millimeters per second) to be practical. Part of the speed limitation was electronic – FLEX 1 had sufficient electrical power to be fast, but the simplified drive electronics wasted as much as 90% of the power and exhibited relatively slow rise and fall times. Further, even if the power issue was fully addressed, the acrylic bowtie actuators were themselves slow and were prone to lifetime and shelf-life failures.

To address the limitations of FLEX 1, a second robot, FLEX 2, using the same basic kinematic design was recently built (see Figure 8). To separate the power and integration issues from the actuator and biomimetic aspects, off-board power was used on FLEX 2. More important, more powerful rolled acrylic actuators were used to replace the previous bowtie actuators. The roll actuators proved better in virtually every respect. Speed was increased from an unimpressive few millimeters per second to a respectable 3.5 cm/s. Lifetime and shelf life were also dramatically improved.

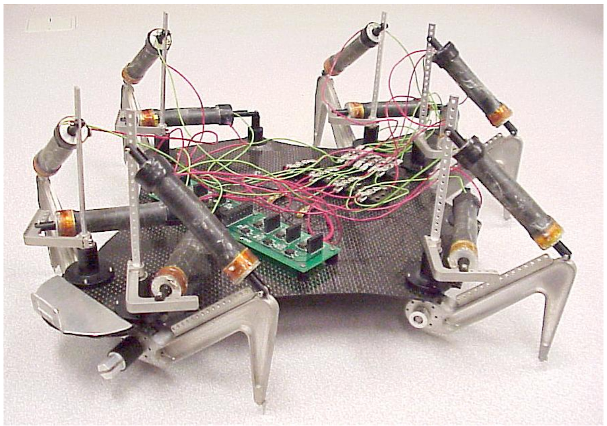

Figure 8. FLEX 2 robot using rolled actuators.

More extensive testing and optimization of FLEX 2 is expected to be completed in the near future. Further increases in speed are expected by optimizing the legs and the actuators' mechanical leverage, and adjusting the timing of the tripod gait. A next-generation legged robot that overcomes the known limitations of FLEX 2 is also planned for this year.

Regardless of these future improvements, FLEX 2 (and the Skitter robot described below) is a milestone in polymer-driven robots. It achieves decent robot performance with genuine lifelike operation. Qualitatively, FLEX 2 has a lifelike locomotion, in contrast to the rigid mechanical-type motion commonly seen in conventional, motor-driven robots. Thus, although much remains to be done to improve speed, obstacle clearance, and integration, FLEX 1 and FLEX 2 illustrate the basic feasibility of implementing biomimetic designs using dielectric elastomers.

Figure 9 shows a different legged robot dubbed Skitter [Pei et al., 2002]. Skitter is based on an earlier pneumatically driven robot dubbed Sprawlita [Clark et al., 2001]. Sprawlita's design was based on the results of research into cockroach locomotion, and in a sense Sprawlita can be described as a "first-order cockroach." Rolled acrylic DE actuators in Skitter were substituted for the pneumatic cylinders in Sprawlita, primarily as an example of the use of this new rolled actuator technology. Skitter uses six rolled actuators to provide six, single-degree-of-freedom legs. This robot was successfully demonstrated and reached a peak speed of approximately 7 cm/s.

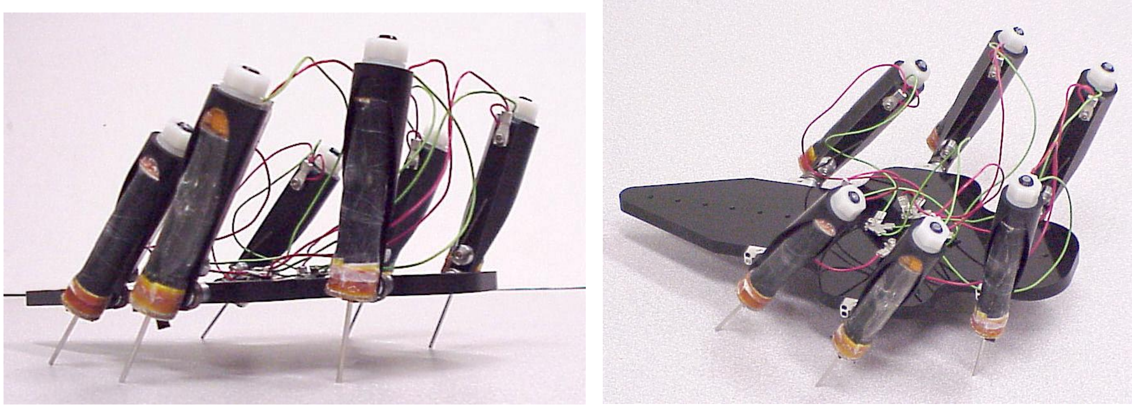

Figure 9. Skitter robot using six rolled actuators.

Unlike the FLEX series robots, Skitter (and the pneumatic Sprawlita) uses legs that can naturally rotate backward about a horizontal axis when an obstacle is encountered in the forward direction. On the other hand, FLEX has two degrees of freedom per leg, which makes it more controllable than the simpler robots (e.g., it can go backward). Thus, planning for the next-generation legged robot focuses on achieving the best features of both biomimetic robots. We also note that the legs of both robots have limited motion for obstacle clearance, a current limitation that should be possible to overcome in future designs.

Figure 10 illustrates yet another biomimetic land robot, an inchworm-type device using silicone dielectric elastomer actuators. The body of the device can stretch and contract, while electrostatic clamps on either end of the robot can be phased relative to the body actuation to make the robot go forward or backward. Because of its design, this type of robot is intended for structured environments (e.g., it is poor on obstacle clearance), but with a suitable surface it can climb vertically. Peak speed is about 1 cm/s, a respectable speed for a device that is only 1.6 cm long.

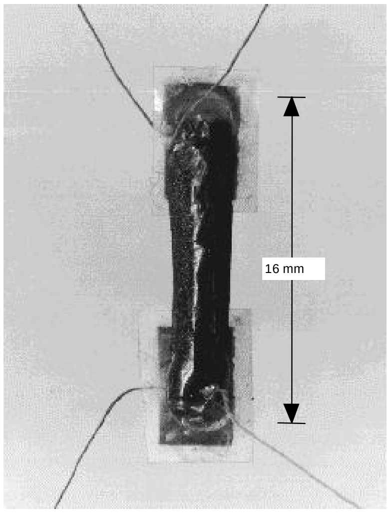

Figure 10. Inchworm-type robot using electrostatic clamps.

Dielectric elastomers may also be used for serpentine manipulators as well as biomimetic grippers. Figure 11 is a CAD drawing of a serpentine manipulator based on DE linear actuators and a proof-of-principle DE test device. More recently, multi-degree-of-freedom roll actuators have been developed that may greatly simplify the design of DE serpentine manipulators [Pei, et al., 2002].

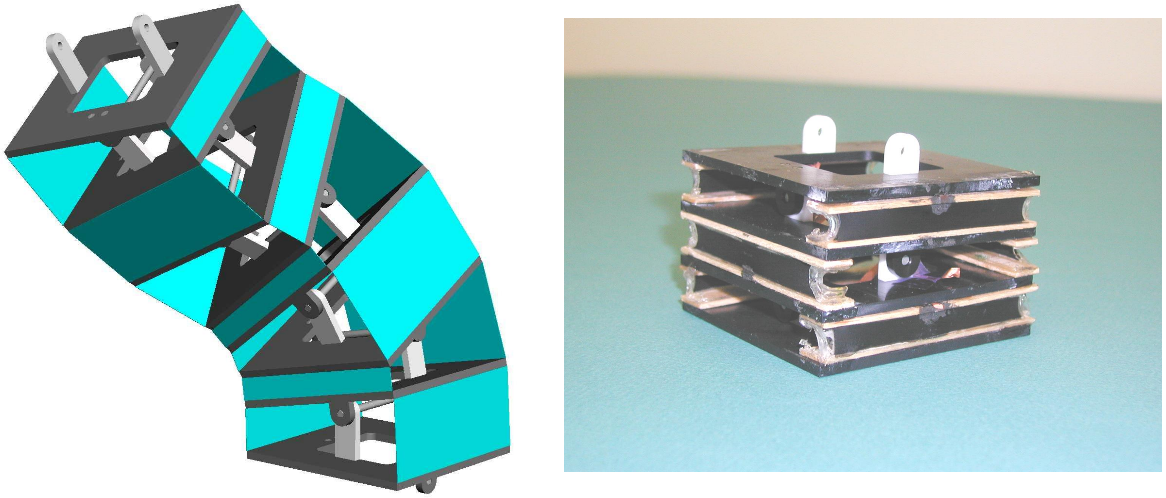

Figure 11. CAD representation of a DE serpentine robot and photo of test device.

Until now we have discussed only land robots, yet biomimetic designs are by no means limited to land locomotion and dielectric elastomers are well-suited for other domains. Figure 12 shows a biomimetic design for a small flapping wing vehicle. Investigation into flapping wing designs illustrates the importance of system-level considerations beyond just the actuator material. Power densities of the silicone or acrylic elastomers used to drive flapping mechanisms are more than sufficient for lift-off. However, the structural support needed for current actuators lowers the total power density dramatically since most designs currently have only 10-20% active dielectric elastomer film mass compared to the weight of the whole actuator. In a sense, the dielectric elastomer mimics the natural muscle itself, but the corresponding “tendon” and “bone” structure and its integration with the dielectric elastomer “muscle” needs further development to reach desired power densities for the entire package.

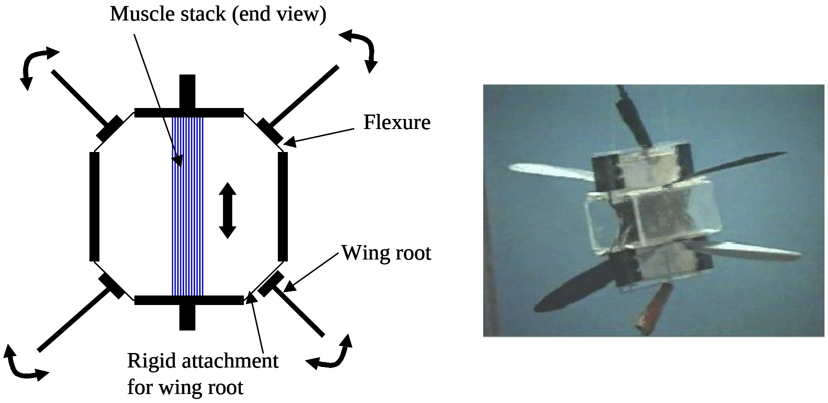

Figure 12. Flapping wing thorax-type design using dielectric elastomers.

Little work has been done to date in swimming biomimetic designs using dielectric elastomer actuators. However, this is an attractive area for dielectric elastomers and electroactive polymers in general. Most realistic underwater swimming devices operate with neutral buoyancy. Otherwise, a significant amount of power is needed just to maintain position under water. Polymers typically have a density about equal to that of water, so they are a natural choice for achieving neutral buoyancy.

Last, there are a great many possible biomimetic applications that do not involve vehicle locomotion. Changing facial expressions, for example, is already being investigated using dielectric elastomers [Pioggia et al., 2001]. Other devices, such as artificial hearts, may benefit from the muscle-like capabilities of dielectric elastomers, and simple nonbiomimetic pumps and valves have already been demonstrated with this technology. Adaptive optics based on biomimetic “eyes” may be a fruitful area.

5. Conclusions

Dielectric elastomer actuators offer an exciting approach for biomimetic designs. While dielectric elastomers are not an exact analogue of natural muscle, they capture many of the important general features of natural muscle such as stress, strain, power density, and elasticity. Further work will undoubtedly improve the match to natural muscle, yet biomimetic design using DE technology may rapidly reach the point where the optimal DE actuator properties are specific to the robot design. That is, one could imagine developing a DE material that has exactly the damping characteristics of a specific cockroach leg muscle, for example, but unless the robot design is a close match to the cockroach in the kinematic and dynamic sense, this damping is unlikely to be optimal.

A number of biomimetic robots have been built by using dielectric elastomers, including legged robots, inchworm-type robots, and flapping wing devices. Rapid progress is being made in a number of areas, as exemplified by the 10X improvement in speed performance of FLEX 2 compared to FLEX 1 built a year earlier. The current generation of dielectric elastomer robots is subjectively achieving many aspects of lifelike motion, and this trend is likely to continue as both the core actuator technology and the robot designs are simultaneously improved.

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