Electroactive Polymer Actuators and Devices

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ABSTRACT

The application of electroactive polymers (EAP) for mechanical actuation is discussed. A comparison is made between established actuation technologies and polymer actuators. In addition, mammalian muscle properties are compared to some of the observed polymer actuation properties. This paper attempts to analyze actuator performance metrics, as set for current technologies, to determine the feasibility of electroactive polymer actuators in various applications. In this analysis, different mechanical design approaches are reviewed for possible use in EAP actuator applications. Examples of EAP microactuators are presented.

Keywords: Electroactive polymers, actuator, actuation, robotics

1. INTRODUCTION

Over the last year, the Defense Advanced Research Projects Agency (DARPA) has begun a major new initiative in the demonstration of electroactive polymers (EAPs) in devices of interest to the Department of Defense (DoD). This initiative has offered a unique perspective on the capabilities and limitations of this interesting class of material. The purpose of this paper is to discuss potential applications for these materials, as well as their current limitations, and to offer a significant challenge to those engaged in the research and development of these materials. No attempt will be made to provide in this paper a detailed understanding of the chemistry and mechanisms of electroactive polymers (EAPs). The papers that follow, as well as many others that have been published,[1-7] address these issues adequately. However, a brief discussion of the characteristics of EAPs is necessary in order to understand the desire of DoD to pursue research in this area.

EAPs are defined here as polymers that can be formulated to have a wide range of electronic and/or electro-optical properties that can be tailored through the chemical composition and structure of the polymers themselves. Interestingly, these properties can often be made to change in response to external stimuli such as applied electric or magnetic field, light, pH, and stress. These changes often manifest themselves in modifications to the physical properties of the polymers, the most important of which is a change in dimension as a result of electrochemical alterations within the polymer – the basis for using these materials as actuators. Because these aforementioned responses are inherent in the internal structure of the polymer, EAPs are in some sense "intrinsically" smart materials.

Table I: Defense Applications for Electroactive Polymers

Actuation and Sensing
- Artificial Muscles
- Smart Skins
- Acoustic (Sonar)
- Biomimetic Devices

Electro-Optical Response
- Analog Processing
- Large Area, Flexible Displays
- Chameleon-like, flexible surfaces
- Polymer FET's

1.1 Applications of Electroactive Polymers

Applications that appear to have the greatest potential for Defense applications fall into two main categories, as shown in Table I. It is important to note that, at least in the authors' opinion, the interesting applications of EAPs do not arise from electroactive properties alone. Though these properties are interesting in and of themselves, there are quite often inorganic counterparts that have similar or even superior properties and usually are more mature. Rather, the uniqueness of these materials for applications arises from the combination of their electroactive properties with the more traditional properties of polymers. Specifically, polymers can be load bearing, easily formed into films and fibers, they are flexible, blendable with other materials and, one hopes, can be produced at relatively low cost. As will be seen, actuation and sensing is a primary example of this combination of electroactive and structural properties. However, even in the second category of applications shown in Table I, the polymeric structure of the material is a critical aspect.

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A brief description of two of the EAP electro-optic applications will serve as examples. The first is the use of the light emitting properties of EAP materials to form flexible LEDs. Dow Chemical is currently supported by DARPA to examine a new family of polymers that exhibit high brightness, and high efficiency at low voltage. Dow has been able to "tune" their polymer system to get EAPs that emit from blue through to red. Though many of the details of this effort are proprietary, there has been some very promising data reported.[8,9] Figure 1 shows some current results for the Dow green emitting polymer system. Once again, there may be inorganic approaches that are more efficient at producing light, but the polymer LEDs potentially have the advantage of being fabricated into flexible films. This flexibility will have obvious payoff to Defense systems in terms of conformal displays or coverings that can change color in a chameleon-like fashion.

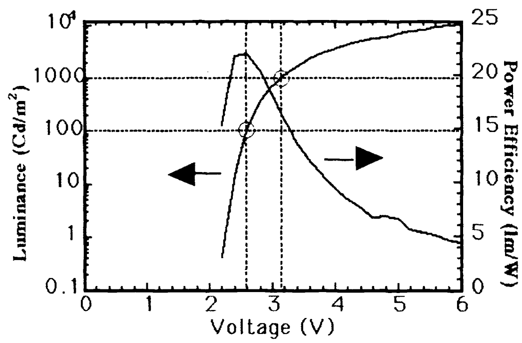

Figure 1. Results on the Dow Green LEP
For 100cd/sqm, efficiency = 21.8 lm/W @ 2.6V
For 1000cd/sqm, efficiency = 16.2 lm/W @ 3.1V

In another effort with Uniax and Raytheon Infrared Center of Excellence (RIRCOE), EAPs are being developed to usher in a new concept for image signal processing. Under this effort, layers of conducting polymers (polyanaline) are being used to form an active resistive network that can be used for analog spatial filtering. Again, specific details are proprietary, but the general concept has been published.[10]

In both of these examples, the primary focus is on the electronic properties of the polymer, but its physical properties are what provides the advantage. This is true to even a greater extent when one considers the use of EAPs as actuators.

2.0 ELECTROACTIVE POLYMER ACTUATION CONCEPTS

This section will briefly discuss the different types of EAP actuators along with some of their limitations. As stated in the Introduction, numerous publications have addressed the basic mechanisms involved in polymer actuators.

In a majority of EAP actuators, the actuation mechanism is based on the movement of an ionic species either in or out of a polymer network. Different types of EAP actuators can be characterized as either gels, ionic polymer metal composites (IPMC) (also called perfluorinated ion-exchange membrane platinum (PIEP)), or conductive polymers.

Gels are crosslinked polymer networks in a solvent. The most common gel actuator is activated by changes in pH (other forms of stimuli can cause the gel to react as well;e.g., heat, light, electrical) that in turn causes ions to move into or out of the polymer structure, thus causing it to swell or contract (Figure 2). This mechanism is characterized by very large volume changes, as much as 1000 fold has been reported.[3] The amount of volume change that can be generated in a gel is directly related to its crosslink density. Gels that have a low crosslink density display large volume change; however the low crosslinking produces a low-modulus gel. This low modulus affects the amount of work that can be generated by the polymer gel. Gels that have a high crosslink density show smaller displacement capability but have a high modulus, and therefore a high capacity for work. The gel actuators have two drawbacks: first, the actuation mechanism is based on ion-diffusion, its speed is transport limited and tends to be low; second, these systems require aqueous solutions for operation.

Gels

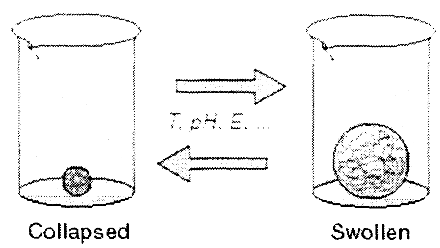

Figure 2. Polymer gel in a solvent

Ionic membrane polymers also rely on transport of ions. These polymer systems are made of an ion conducting membrane material, such as Nafion, that is plated with metal electrodes (for example, platinum). One popular system is the ion-exchange polymer metal composite (IPMC) actuator.[4,5] By applying an electric field to the membrane, ions can be moved from one surface (electrode) to the other, causing the membrane to move. While the actual mechanism is not perfectly understood, it appears that the ion mobility causes expansion of one side of the material and a commensurate contraction of the other. Because the ions are moving within the material, transport is more localized than in polymer gels. Again, the mechanism is diffusion limited and requires an aqueous solution. The hope for these materials is that they can be sealed and, more importantly, that their response time can be improved (possibly by controlling the diffusion distance necessary for actuation). While the IPMC actuators are stiffer than gel actuators, the IPMC materials demonstrated to date tend to be very soft, and thus may have limitations in work-performing ability.

Conducting polymers are similar in principle to the IPMCs and gels in that ion movement causes a dimensional change in the material. Conduction in these polymers is based on incorporating a dopant species (anion or cation) into the polymer network.[1,6] These dopant species modify the polymer's electrical as well as its mechanical properties. Furthermore, by applying an electrochemical potential to the polymer, dopant insertion and deinsertion can occur. This movement of ions in and out of the polymer network leads to dimensional changes that can be used for actuation. As in the above systems, conducting polymers require an anode, cathode, and an electrolyte. The electrodes can be fabricated out of the conducting polymer material, making the actuator components chemically and mechanically compatible.

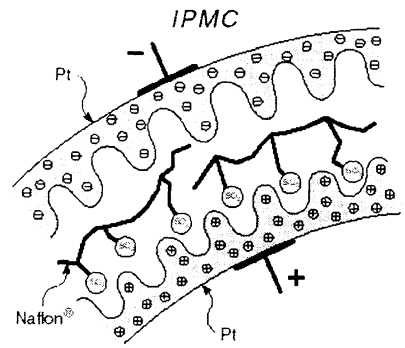

Figure 3. Showing the microstructure of IPMC actuator

Electrostrictive polymers come in two forms. The first form is an actuator based on electrostriction of a polymer dielectric sandwiched between two compliant electrodes.[11] At high electric fields, a large electrostatic force is generated between the electrodes which compresses the dielectric material. Since the materials used to build these actuators are compliant, the actuators can be rolled into cylindrical shapes to provide axial displacements. Electrostrictive actuators based on this approach have demonstrated very fast response rates. However, these actuators require high voltages to operate, which causes integration problems at the system level. Another form of actuation is based on electrostrictive polymers that function on a phase transition principle. Penn State has been engineering poly(vinylidene difluoride-co-trifluouoethylene (P(VDF-TrFE)) co-polymers that exhibit improved strain capability over existing EAPs.[7] The actuation properties of these co-polymers are based on a phase transition (ferroelectric to paraelectric) that these materials undergo. This phase transition leads to a large lattice change within the material which generates large volume changes. Initial data on the P(VDF-TrFE) actuators show a 4% strain capability with <15MPa stress generation.

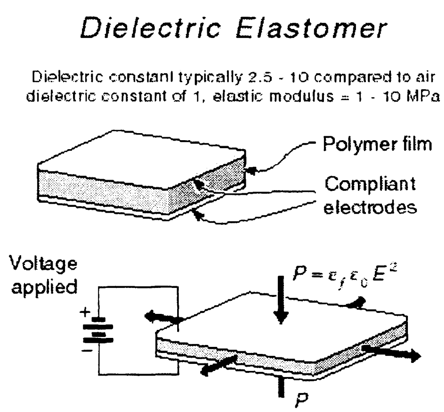

Figure 4. Illustrates the electrostrictive polymer actuator

3.0 THE CHALLENGE FOR EAP ACTUATORS

From the onset, it is valid to ask why one should investigate polymer-based actuators when there is a plethora of other actuator technologies already being used in device designs, and polymer actuators are in their infancy. In short, where is the niche for this class of actuators that would warrant major efforts to develop them?

To answer this question, one needs to examine the performance of existing actuator technologies and to make a general comparison to electroactive polymer systems under development. In examining the actuator characteristics of existing systems, a set of performance metrics can be generated to guide the development of EAP actuators. Established technologies consist of electromagnetic, pneumatic, and hydraulic actuators, each delivering a varying degree of power/mass and force/mass performance. Newer actuator technologies are emerging and include piezoelectric ceramics, magnetostrictive materials, and shape memory alloys. For reasons that will shortly become clear, mammalian muscle is also included in this discussion.

3.1 Comparison of Actuation Technologies

When considering actuation systems for robotics (macro, micro and nano), autonomous vehicles, and general gross and fine actuation needs, it is important to realize that the actuation requirements can and will dominate the overall mechanical design (system level). Therefore, it is difficult to establish the "best" characteristics for an actuation system without considering the specific application. That said, there are several characteristic performance metrics that designers can use to evaluate and compare actuation performance.

The first, shown in Figure 5, is stress versus strain for various actuators. Included in this graph is a set of force density curves.[c] (Essentially this chart shows the force that an actuator can apply, for a given strain). In examining the stress versus strain properties of various actuators, it can be seen that the actuators providing the largest displacements exhibit the lowest stress. Likewise, the actuators that have a large stress capability have relatively low displacement ability. Shape memory alloys (SMA) and hydraulic actuators demonstrate large stress and strain capability. However, SMAs are mechanically inefficient, due to poor conversion of thermal energy into mechanical energy, approximately 2-3%.[12] Hydraulic actuators provide impressive performance and have been extensively implemented in robotic designs. One major drawback with hydraulic systems is the large overhead (pumps, piping, support structure) associated with them that impacts their applicability for small scale devices.

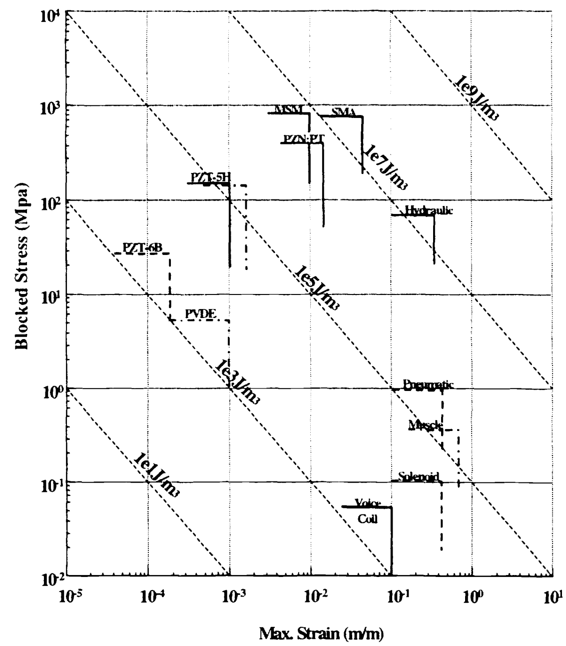

Figure 5. Stress vs. Strain for various actuator technologies (Included are force density curves)

Another important metric of an actuator is its ability to do work coupled with the rate over which that work can be done, i.e., power. There are numerous ways to examine actuator parameters and, of course, the ultimate performance that matters is at the systems level. Figure 6, which shows the relationship between specific work and actuation frequency (bandwidth) for different types of actuators, is a reasonable representation of performance metrics at the sub-system level.[a] Included in Figure 6 are power/mass curves for comparing actuators that have different bandwidths of specific work capability. In addition, this chart indicates that many actuators that have a high specific work capability also have a limited bandwidth. Similarly, actuators with high bandwidth have a tendency to exhibit low specific work properties.

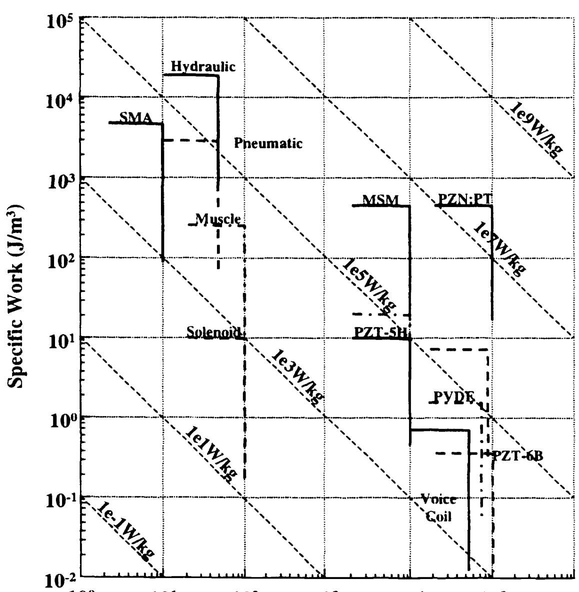

Figure 6. Work vs. Frequency for various actuator technologies (included are power/mass curves)

From this brief analysis, it is clear that there is a wide range of actuator concepts that span a very large "performance space." Based on that, it is apparent that the promise of any new actuator concept has to be based on more than just one performance metric. This is the case with EAP actuators.

Currently, robotic platform and a range of other actuation-based devices use piezoelectric actuation, motors, gears and pulleys. However, at least from a Defense interest point of view, there appears to be a significant advantage to develop

[c] Chart has been generated by Defense Science Research Council for DARPA (unpublished)

actuators that emulate biological functions, e.g., swimming with the stealth of a lamprey,[d] or emulating the hovering ability of an insect. These advantages appear to be especially important as one builds smaller and smaller devices, something that nature is obviously very good at. In those cases, it is not clear that conventional actuation schemes will suffice. What is really needed are actuation schemes that are soft and flexible, allowing easy integration into bio-inspired devices. Of the possible actuation technologies, only those based on polymers appear to have a chance to fulfill this need. It is the authors' opinion that their promise lies in two related aspects: first, EAP's ability to emulate the function of natural muscles; second EAPs are mechanically simple, allowing them to be used for microactuation.

3.2 Quintessential Actuator – Natural Muscle

Many robotic designs are bio-inspired. We marvel at the mechanical systems found in nature, and realize that mammalian muscle is an actuation system that has impressive attributes that include, self healing and scalability. It is amazing that skeletal muscles, across all species of mammals, have the same structure. The difference between our muscles and those of the elephant is in the muscle bundle make-up --- the elephant has many more muscle fibers per bundle than found in human muscles. These observations have lead many investigators to seek an actuation system that mimics the natural fiber architecture found in mammals. It is this approach that makes polymers attractive for actuators. The flexibility in manufacturing polymer fibers, and their intrinsic properties for actuation and sensing, affords us the opportunity to engineer actuators that imitate nature. Table II depicts the target that natural muscle presents for the EAP actuator designer. As a specific example, the muscle of a dragonfly muscles operate at a frequency of 30-40Hz with a specific work of about 60-100 W/kg.[13]

Table II Characteristics of Natural Muscle

Specific Energy	100-500 J/kg
Specific Work	~ 1 kW/kg
Frequency Response	< 500 Hz
Elongation	>40%

3.3 Micro Actuation:

A very good discussion on microactuators (i.e., actuators of size ~1mm^3) can be found in Fearing.[14] This paper reviews the fundamental performance limitations encountered when scaling down actuators for mm-scale operation. In the macro-robotic regime, figures of actuation merit are in terms of power/mass and force/mass parameters. However, when the scale for the robotic actuator approaches the mm range, then the overhead penalty (power supplies, pumps, fixtures, ect.) of these macro-actuator may be too great, and system power density may become a more discriminating metric. Fearing claims that for micro-robotic applications, one should consider actuators that have reasonable speed, high force, and large displacement capability. To further illustrate his point, Fearing calculates the power density needed for a swimming, running and flying micro-vehicle and concludes that their power density requirements range from 20 W/m to 2 x 10^3 W/m. In addition, he shows how for selected actuators their power density decreases with decreasing size. It is the authors' opinion that this makes EAP actuators an ideal candidate for such small systems.

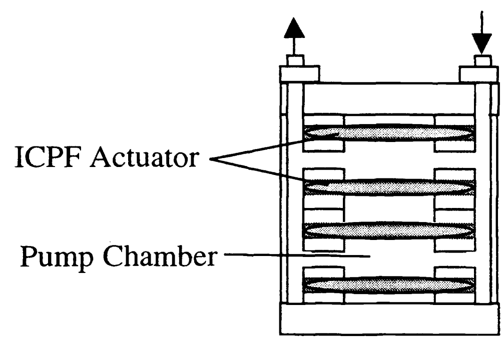

Figure 7. Micropump utilizing EAP polymers, designed and built by Gou.

Knowing the target space for EAP actuators is certainly beneficial to the development of the materials themselves. It is not reasonable and not even useful to try to have EAPs compete with other actuation concepts in applications for which they are ill-suited. However a serious question arises about whether the promise of EAP actuators can live up to the needs even in these limited, albeit important applications. This is the thrust of the remainder of the paper.

[d] The lamprey swims by "corkscrewing" through the water, eliminating the wake, one of the major sources for detecting undersea vehicles.

4.0 EAP ACTUATORS – THE PROMISE

4.1 EAP in Microactuator Applications

Kornbluh demonstrated a spherical joint actuator and a rotary motor using electrostrictive polymer muscles.[11] Smela, using micromaching techniques and conducting polymer actuators (hinge actuators) built an array of folding boxes (300 microns on a side) that danced under an applied electric field.[15] Bar-Cohen has been aggressively exploiting IPMCC technology for tele-robotic applications (particularly for space operation).[4] Bar-Cohen has designed and fabricated a robotic gripper for manipulation or picking up rocks on extraterrestrial bodies, and a lens wiper for cleaning optical elements during planetary exploration. Mojarrad and Shahinpoor have fabricated and demonstrated a robotic swimming robot based on the IPMC actuator.[5]

Size	12mm x 20 mm
Weight	4.1 g
Material	Stainless
Flow	4.5 microliters (rated) 37.8 microliters (max)
Actuator	ICPE Actuator
Power	AC 1.5V, .14A

Table III. Performance of Micro Pump utilizing EAP actuators

Several very interesting as well as inspiring EAP actuator applications are being reported from Japan.[16,17] Guo, has designed and built a micro pump using ionic conducting polymer film (ICPF) which is very similar to the IPMC material.[16] The ICPF actuator is made from perfluorosulfonic acid polymer (Nafion) and has plated platinum electrodes as in the IPCM system. The actual chemical modifications to the perfluorosulfonic acid polymer is not known; however, the actuator performance is very similar to the IPMC system. The micro pump utilizes ICPF actuators as diaphragms to create a volume change in the pump chamber. The basic design allows for multiple chambers to increase flow rates (Figure 7). The actuators are driven by a sinusoidal voltage in order to deliver continuous pumping. The performance specifications for this micro pump are shown in Table 3.

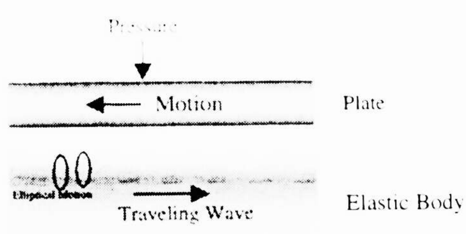

Figure 8. Principle behind ultrasonic motors

Another interesting application of EAP actuators has been in the fabrication of an elliptic friction drive element for a motor.[17] Tadokoro has designed and demonstrated a motor concept, very similar to ultrasonic motors, that uses ICPF actuators to generate traveling waves in both the support plate and rotor. Figure 8 illustrates the drive principle active for an ultrasonic motor or linear actuator. The principal drive mechanism comes from setting up standing waves in an elastic body. These plate waves effectively set up a tangential force that can push a rotor or a plate. Tadokoro has been able to fabricate an elliptical friction drive (EFD) that simulates a segment or element of the piezoelectric plate. Figure 9 shows how the EFD is constructed: a strip of the perfluorosulfonic acid membrane (PFSF), attached to the ICPF actuators, acts like an element of the piezoelectric plate, and is capable of providing a localized sinusoid force. A set of these actuators, working in unison, can reproduce the same effect of the piezoelectric plate wave. This set of EAP actuators could be configured to drive a rotor or a linear element. Figure 10 is one of Tadokoro concepts for a linear actuator.

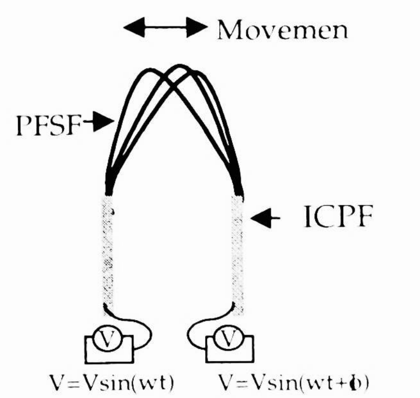

Figure 9. EFD Actuator based on EAP materials

From the above examples, it can be seen that ionic polymers are being used for microactuation. Another EAP system that has the potential to make a significant impact in the micro-actuation area are the electrostrictive co-polymers (P(VDF-TrFE). Preliminary results on these co-polymers indicate that they have a large strain level (>4%) and an energy density of 3×10^5 J/m^3. These figures of merit exceed piezoceramics that are under consideration for micro-actuator applications. It is not unreasonable to

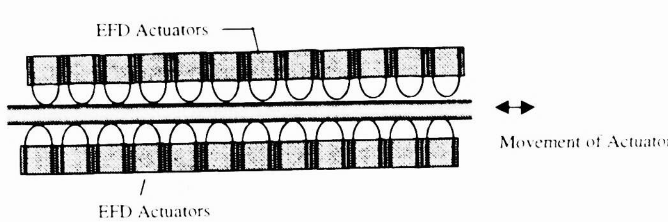

Figure 10. Tadokoro's concept for a linear actuator using EFDs

consider the family of EAP actuators (gels, conducting polymers and electrostrictive) as having the potential to meet the formidable actuation requirements needed for micro-robotics.

4.2 Performance of EAP

As described above, EAP actuators have been demonstrated in small scale and in limited cases. However, their pervasive application, especially as artificial muscles, is still limited by the performance of the polymer materials.

Table 4 provides a summary of the advantages and the disadvantages of the various approaches, for EAP actuators. It also shows the general stress/strain characteristics as provided by researchers in the field. As a general class of actuators, it would appear that EAPs may be competitive in mechanical performance with many of the other actuator technologies described earlier in this paper. However, a word of caution is in order for the EAP data set. These data are preliminary, and much more characterization is needed. As seen in Table 4, the fundamental mechanisms providing the actuation are not fully understood, the robustness and stability of these polymer systems have not been established, and overall mechanical properties have not been carefully measured. However, both the promise and the

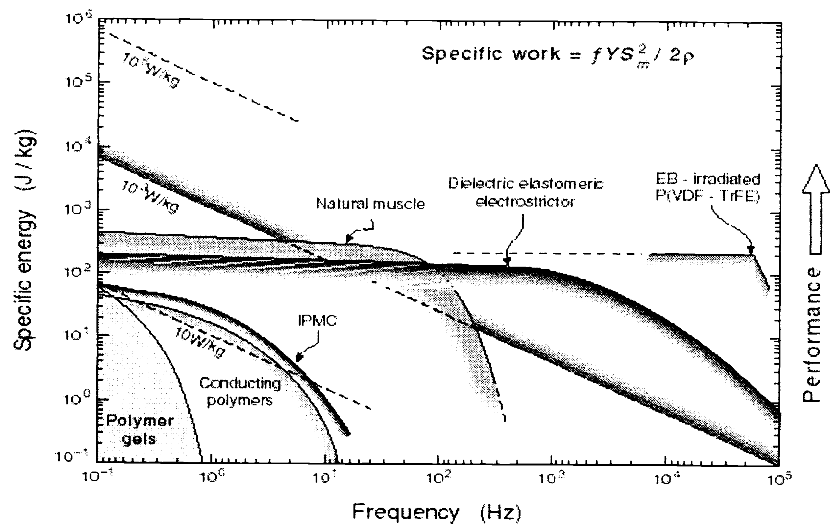

Figure 11. Illustrating how EAP actuators energy and bandwidth compare to mammalian muscle

Table IV – Review of EAP Actuators, performance Limitations and Issues

Actuation Mechanism	Performance	Advantages	Critical Research Issues
Gels	Stress: .1-.3 MPa Strain: +1000%	Well understood mechanisms. Large volume changes. Light or ph activated.	Slow response times. Transport without liquid desired. Higher work capacity needed.
Ionic Polymers	Stress: .1- 1MPa Strain: 1-10%	Muscle-like behavior demonstrated. Easily processed/formed. Large deformations possible	Poor understanding of processing-property relationships. Higher speeds and work capability desired.
Conducting Polymers	Stress: 450MPa Strain: 1-10%	Well understood mechanisms. Reasonable deformations and forces demonstrated. Interesting constructions possible	Difficult to process. Ability to Construct an actuator device limited.
Electrostrictive Polymers	Stress: .2-2 MPa Strain: 10-30%	Small strains, but very large forces expected. Easy to make into acoustic actuators	Elimination of hysteresis effects. Determination of processing – property effects.

shortfalls of EAP actuators are clearly demonstrated when the performance of EAPs is matched against that of muscle. This comparison is shown in Figure 11.

First to be considered are electrostrictive polymers. A cursory examination of the performance appears to indicate that they are perfect actuator materials. However, on closer examination, one observes that the best performance is at frequencies in excess of those usually necessary in "muscle" applications. More importantly, the voltage required to activate these materials is on the order of hundreds of volts. The high voltage requirement has not prohibited the use of these actuators.[11] However, it does make actuation design more complicated.

The remaining actuators, gels and ionic and conducting polymers, perform well at very low frequencies, but are severely limited by their inability to operate at higher frequencies. This is undoubtedly due to the mechanism of transport within the material. Another limitation is that the force that can be generated at large strains appears to be limited by the low modulus of the materials. Further, the current systems require aqueous transport, which can be a limitation in the operational use. Therefore, the critical question that must be answered by research is whether these are fundamental limitations of the actuation mechanisms, or whether clever design and chemistry can be used to surmount these limitations.

5.0 SUMMARY

The above discussion illustrates both the promise and the challenges with EAP actuators relative to established technologies. Significant work remains to be done towards understanding the mechanisms of EAP actuation and their effect on performance. The available mechanical, chemical and electrical data on polymer actuators is incomplete. Research work needs to focus on: developing a comprehensive understanding of the polymer actuation mechanism, generating a complete set of mechanical properties for EAPs, investigating the robustness and reliability, and developing a set of design rules for utilizing EAPs as actuators.

Furthermore, during the development of EAP actuators, it is important to keep in mind the end application. There are many examples of robotic actuator systems based on less than optimal actuation technologies. For examples, design trade-offs used to improve SMA's bandwidth (in some cases by 400%) can be found in the literature.[18-20] Similar approaches should be applicable for EAP, which will allow this new class of actuators to achieve the necessary properties for use in robotic and microactuation systems.

There are some applications where EAP materials are already making a mark. But, if the holly grail of artificial muscle is to be achieved, further research on these materials will be necessary.

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