Artificial Muscles using Electroactive Polymers (EAP): Capabilities, Challenges and Potential

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For decades, EAP received relatively little attention due to their limited actuation capability. However, in the last fifteen years a series of Electroactive Polymers (EAP) materials have emerged that produce a significant shape or size change in response to electrical stimulation. These materials have the closest functional similarity to biological muscles enabling to engineer novel capabilities that were impossible to do up until recently. Efforts are underway to address the many challenges that are hampering the practical application of these materials and recent progress already led to dramatic capability improvements. Various novel mechanisms and devices were demonstrated including robot fish, catheter steering element, robotic arms, miniature gripper, loudspeaker, active diaphragm, Braille display, and dust-wiper. For developers of future medical devices these materials are offering numerous advantages for their flexibility, fracture toughness, and controllability, as well as low mass and low power requirements. This paper provides a review of the current status, the challenges and potential near future applications of these materials.

Keywords: Artificial Muscles, Electroactive Polymers, EAP, Biomimetics, Polymer Actuators, Robotics

Background

Natural muscles are one of the most important actuators in biological systems that are larger than a bacterium. The fact that, with a very small difference between species, muscles are fundamentally driven by the same mechanism in all animals suggests that they are highly optimized. Electroactive polymers (EAP), which emerged in the last fifteen years exhibiting large strain in response to electrical stimulation, are human made actuators that most closely emulate muscles. For this response, EAP have earned the moniker “artificial muscles” [1]. The impressive advances in improving their actuation strain capability are attracting the attention of engineers and scientists from many different disciplines. They are particularly attractive to biomimetic experts since they can be used to mimic the movements of humans, animals and insects for making biologically inspired mechanisms, devices and robots [2]. Increasingly, engineers are able to develop EAP actuated mechanisms that were previously considered unimaginable.

For many decades, it has been known that certain types of polymers can change shape in response to electrical stimulation [3-4]. Initially, these EAP materials were capable of producing only a relatively small strain. However, since the beginning of the 1990s, new EAP materials have emerged that exhibit large strains and they led to a great paradigm change with regards to the capability of electroactive polymers and their potential [1]. Generally, EAP materials can generate strains that are as high as two orders of magnitude greater than the striction-limited, rigid and fragile piezoelectric ceramics. Further, EAP materials are superior to shape memory alloys (SMA) in higher response speed, lower density, and greater resilience. They can be used to make mechanical devices without the need for traditional components like gears, and bearings, which are responsible for their high costs, weight and premature failures. The current limitations of EAP materials that include low actuation force, mechanical energy density and robustness are constraining the practical application but improvements in the field are expected to overcome these limitations.

In 1999, in recognition of the need for international cooperation among the developers, users, and potential sponsors, the author initiated a related annual SPIE conference as part of the Smart Structures and Materials Symposium [5]. This conference was held in Newport Beach, California, USA, and was the largest ever on this subject, marking an important milestone and turning the spotlight onto these emerging materials and their potential. The SPIE EAP Actuators and Devices (EAPAD) conferences are now organized annually and have been steadily growing in number of presentations and attendees. Also, the author is issuing electronically the semi-annual WorldWide ElectroActive Polymers (WW-EAP) Newsletter covering the latest news and advances [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html], and he is managing a website that archives related information that includes links to homepages of EAP research and development facilities worldwide [http://eap.jpl.nasa.gov]. In the past few years, in addition to the SPIE conferences, several other conferences and special sessions within conferences focusing on electroactive polymer actuators have also taken place.

Electroactive Polymers (EAP)

There are many EAP materials [1]. In order to make a clear distinction between their activation mechanisms, the author divided them into two major groups including: ionic (involving mobility or diffusion of ions) and electronic (driven by electric field or Maxwell forces) [1 & 6]. The currently available leading EAP materials are listed in Table 1 and a summary of the advantaged and disadvantages of these two groups of materials are listed in Table 2. The electronic polymers (electrostrictive, electrostatic, piezoelectric, and ferroelectric) can be made to hold the induced displacement under activation of a DC voltage, allowing them to be considered for robotic applications. Also, these materials have a greater mechanical energy density and they can be operated in air with no major constraints. However, they require a high activation field (>100-V/μm) close to the breakdown level. In contrast, ionic EAP materials (gels, polymer-metal composites, conductive polymers, and carbon nanotubes.) are driven by diffusion of ions and they require an electrolyte for the actuation mechanism. Their major advantage is the requirement for drive voltages as low as 1-2 Volts. However, there is a need to maintain their wetness, and except for conductive polymers and carbon nanotubes, it is difficult to sustain DC-induced displacements. The produced displacement of both the electronic and ionic EAP can be geometrically designed to bend, stretch or contract. Any of the existing EAP materials can be made to bend with a significant curving response, offering actuators with an easy to see reaction and an appealing response. However, bending actuators have relatively limited applications due to the low force or torque that can be induced.

TABLE 1: List of the leading EAP materials

Electronic EAP	Ionic EAP
▪ Dielectric elastomer EAP ▪ Electrostrictive Graft Elastomers ▪ Electrostrictive Paper ▪ Electro-Viscoelastic Elastomers ▪ Ferroelectric Polymers ▪ Liquid Crystal Elastomers (LCE)	▪ Carbon Nanotubes (CNT) ▪ Conductive Polymers (CP) ▪ ElectroRheological Fluids (ERF) ▪ Ionic Polymer Gels (IPG) ▪ Ionic Polymer Metallic Composite (IPMC)

TABLE 2: A summary of the advantages and disadvantages of the two basic EAP groups

EAP type	Advantages	Disadvantages
Ionic EAP	• Natural bi-directional actuation that depends on the voltage polarity. • Some ionic EAP like conducting polymers have a unique capability of bi-stability • Requires low voltage	• Requires using an electrolyte • Electrolysis occurs in aqueous systems at >1.23 V • Require encapsulation or protective layer in order to operate in open air conditions • Low electromechanical coupling efficiency. • Except for CPs and NTs, ionic EAPs do not hold strain under dc voltage • Slow response (fraction of a second) • Bending EAPs induce a relatively low actuation force • High currents require rare earth electrodes such as gold or platinum • Except for CPs, it is difficult to produce a consistent material (particularly IPMC)
Electronic EAP	• Exhibits high mechanical energy density. • Induces relatively large actuation forces • Can operate for a long time in room conditions • Exhibit rapid response (mSec) • Can hold strain under DC activation	• Independent of the voltage polarity, it produces mostly monopolar actuation due to associated electrostriction effect. • Requires high voltages (~100 MV/m). Recent development allowed for a fraction of the field in the Ferroelectric EAP

EAP materials characterization

Construction of mechanisms or devices that are actuated by EAP materials requires accurate and detailed information about the properties of the materials that are used [7]. In order to assess the competitive capability of EAPs, there is a need for a performance matrix that consists of comparative performance data. Such a matrix needs to show the properties of EAP materials as compared to other classes of actuators, including piezoelectric ceramic, shape memory alloys, hydraulic actuators, and conventional motors. Studies are underway to define a unified matrix and establish effective test capabilities [7]. Test methods are being developed to allow measurements with minimum effect on the EAP material. While the electromechanical properties of electronic-type EAP materials can be addressed with some of the conventional test methods [6 and 7], which are used for example to test piezoelectric materials, the ionic-type EAPs (such as IPMC) are posing technical challenges. The response of these materials suffers complexities that are associated with the mobility of the cation on the microscopic level, strong dependence on the moisture content, and hysteretic behavior. The use of a video camera and image processing software offers an effective capability to study the deformation of IPMC strips under various mechanical loads. Simultaneously, the electrical properties and the response to electrical activation can be measured. Nonlinear behavior has been clearly identified in both the mechanical and electrical properties and efforts were made to model this behavior [6 and 7].

Applications of EAP

As polymers, EAP materials have a lot of attractive properties that are superior to other actuation materials. EAP can be easily formed in various shapes, their properties can be engineered and they can potentially be integrated with miniature sensors to produce smart actuators. Unfortunately, the existing EAP materials are still exhibiting low conversion efficiency, are not robust, and there are no standard commercial materials available for consideration in practical applications. In order to take these materials from the development phase to application as effective actuators, the field infrastructure is being established address the science, engineering, and manufacturing [1] issues as well as the commercial availability of these materials for wider use.

In recent years, there has been significant progress in the field of EAP toward making practical actuators, and commercial products are starting to emerge. At the end of 2002, the first milestone product was announced by Eamax, Japan, and it is in the form of a fish robot. Moreover, many organizations are exploring potential applications for EAP materials for such areas as medical, robotics, exoskeletons, articulation mechanisms, aerospace, automotive, entertainment, animation, toys, clothing, haptic and tactile interfaces, noise control, transducers, power generators and smart structures. Some of the applications that are considered include:

Medical applications and potential artificial organs

Using EAP materials as actuators of artificial organs and limbs is involved with significant challenges including functional compatibility, rejection avoidance, and ability to meet the stringent requirements that are associated with the use of these materials on or in humans. At present, the electronic EAP materials seem to be the most applicable since they generate the largest actuation forces and they have the highest robustness. However, the required voltages that can be as high as several thousands of voltage pose potential hazard that must be addressed. Even though the electric current is relatively low, the use of high voltages can cause blood clots or injury due to potential voltage breakdown and shorting to the body. On the other hand, the ionic EAP group is chemically sensitive requiring effective sealing for protection of the internal organs and avoiding contamination of the ionic content, which reduces the performance efficiency. Also, it is difficult to maintain their static position, particularly for the IPMC, because of the fact that these materials involve chemical reaction and even DC voltage causes a reaction.

Interfacing between human and machine to complement or substitute our senses can enable important capabilities for medical applications. A number of such interfaces were investigated or have been considered and the most significance work is in area of interfacing machines and the human brain. A development by scientists at Duke University [8-9] as well as Caltech, MIT, Brown University, and many other research institutes enabled this possibility where electrodes were connected to the brain of a monkey, and, using brain waves, the monkey operated a robotic arm. If EAP actuated robotic arms are developed with sufficient strength and dexterity to function as effective prosthetics then this development by neurologists would help disabled people greatly. Using such interfacing capability to control prosthetics would require feedback to allow the human user to "feel" the artificial limbs. The required feedback can be provided with the aid of tactile sensors, haptic devices, and other interfacing mechanisms. Besides providing feedback, sensors will be needed to allow the users to protect the prosthetics from potential damage from heat, pressure, impact, and others just as we do with our biological limbs. The development of EAP materials that can provide tactile sensing is currently under way as described in [1]. Other areas of medicine that are benefiting from the development in EAP include robotics as discussed in the next section.

Biomimetic robots

Engineering an artificial limb, face and other parts of the body that appear and functions as realistic as the biological organs is a significant challenge due to the physical and technological constraints and shortcomings of the available technology. The use of effective artificial muscles, artificial intelligence and other biomimetic technologies are expected to make the possibility of realistically looking and behaving organs more practical engineering models [2]. Further, using this technology would allow making robots that are more accurate copies of the original creatures. The capability to produce EAP in various shapes and configurations can be exploited using such methods as stereolithography and ink-jet processing techniques [10]. Potentially, a polymer can be ejected drop-by-drop onto various substrates. Such rapid prototyping processing methods may lead to mass-produced robots in full 3D details including the actuators allowing quick transition from concept to full production [1].

To mimic a biological hand using simple elements, the author and his coinvestigators constructed a miniature robotic arm that was lifted by a rolled dielectric elastomer EAP as a linear actuator and four IPMC-based fingers as a bending actuator [1]. The linear actuator was used to raise and drop a graphite/epoxy rod that served as a simplistic representation of a robotic arm. As shown in Figure 1, this gripper grabs rocks very similar to the human hand.

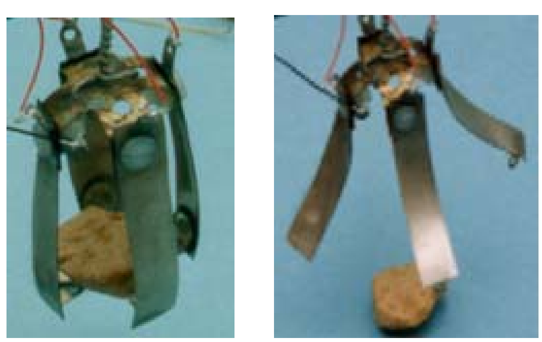

FIGURE 1: 4-finger EAP gripper lifting a rock.

Using EAP actuators, biologically inspired robots may be developed with capabilities that are far superior to natural creatures since they are not constrained by evolution and survival needs. These robots can be used in such configurations as octopus to perform multiple tasks simultaneously or operate as worms to travel thru the human body and perform various surgical procedures that can be performed either autonomously or wirelessly controlled. Important addition to this capability can be the application of tele-presence combined with virtual reality using haptic interfacing. The use of electrorheological fluids was proposed for the development of haptic interfaces [11]. Using such an interface for a simulator aided by virtual reality can potentially benefit medical therapy in space and at distant human habitats. The probability that a medical urgent care procedure will need to be performed in space is expected to increase with the growth in duration and distance of manned missions. A major obstacle may arise as a result of the unavailability of on-board medical staff capable of handling every possible medical procedure that may be required. To conduct emergency treatments and deal with unpredictable health problems the medical crews will require adequate tools and capability to practice the necessary procedure to minimize risk to the astronauts. With the aid of all-in-one-type surgical tools and a simulation system, astronauts with medical background would be able to practice the needed procedures and later physically perform the specific procedures. Medical staff in-space may be able to sharpen their professional skills by practicing existing and downloaded new procedures. Generally, such a capability can also serve people who live in rural and other remote sites with no readily available full medical care capability. As an education tool employing virtual reality, training paradigms can be changed while supporting the trend in medical schools towards replacing cadaveric specimens with computerized models of human anatomy.

Recent milestone for the Field

The field of EAP has been advancing rapidly in the last few years and major milestones were made including:

a. In Dec. 2002, the first commercial product has emerged having the form of a Fish-Robot (Eamex, Japan). An example of this Fish-Robot can be seen on [http://eap.jpl.nasa.gov] where there is also a link to a video showing Fish-Robots swimming in a fish tank. It swims without batteries or a motor and it uses EAP materials that simply bend upon stimulation. For power it uses inductive coils that are energized from the top and bottom of the fish tank.
b. On March 7, 2005, the first arm wrestling contest took place between a human opponent and three robotic arms driven by EAP actuators. This content was in response to the 1999 challenge posed to the worldwide engineers by the author in an effort to promote worldwide development for the realization of the potential of EAP materials [1]. A graphic rendering of this challenge that was posed by the author is illustrated in Figure 2. Success in developing such a winning arm will lead to many important applications including the possible use of EAP to replace damaged human’s muscles, i.e., making "bionic human." It will also enable biomimetic capabilities that are currently considered impossible. It would allow applying EAP materials to improve many aspects of our life where some of the possibilities include smart implants and prosthetics (also known as cyborgs), active clothing [12], realistic biologically-inspired robots [2] as well as fabricating products with unmatched capabilities.

The intent of posing this challenge was to use the human arm as a baseline for the implementation of the advances in the development of EAP materials. During the contest, which has been a significant event for the field, a 17-years old female student wrestled with three robotic arms driven by EAP. These arms were made by Environmental Robots Incorporated (ERI), New Mexico; Swiss Federal Laboratories for Materials Testing and Research, EMPA, Dubendorf, Switzerland; and three senior students from the Engineering Science and Mechanics Dept., Virginia Tech. The arms and the results were as follows:

FIGURE 2: An artistic interpretation of the Grand Challenge for the development of EAP actuated robotics.

1. The arm held for 26-second against the student. This wrestling arm (see Figure 3) had the size of an average human arm and it was made of polypropylene and Derlin. This arm was driven by two groups of artificial muscle. One group consisted of dielectric elastomeric resilient type that was used to maintain an equilibrium force and the second was composed of ionic polymer metal composites (IPMC) type strips that flex to increase or decrease the main resilient force.

FIGURE 3: The ERI arm wrestling with the 17-year old human opponent, Panna Felsen. This arm has the size of an average human arm and it held for 26-seconds against Panna.

2. The Swiss arm (Figure 4) was able to resist for 4-seconds before losing. This arm was driven by the dielectric elastomer EAP type using multi-layered scrolled actuators that were organized in 4 groups. A photo of one of the group lifting two 5-gallon water containers (about 20-kg) is shown in Figure 5. These actuators were operated similar to

human muscles, where two of these groups acted as protagonists and the other two operated as antagonists. The arm had an outer shell made of fiberglass that was used as a shield for the electric section. The arm structure was made of composite sandwich consisting of fiberglass and carbon fibers.

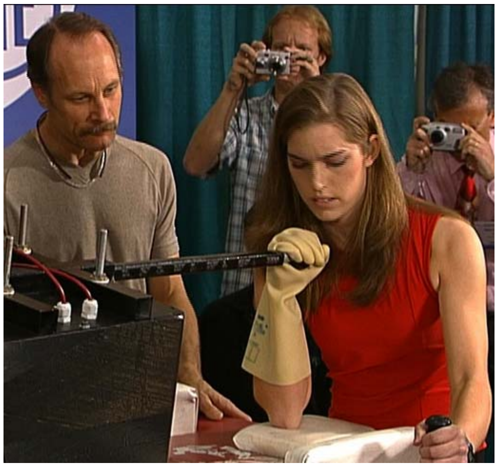

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FIGURE 4: The Swiss company, EMPA, arm is shown wrestling with the student. The rubber glove that the Panna is using provided her electrical insulation for protection.

FIGURE 5: One of the groups of EMPA's EAP actuators is shown lifting two 5-gallon water containers.

3. The VT arm (Figure 6) managed to hold for 3-seconds. The EAP actuator of this arm was constructed of polyacrylonitrile (PAN) gel fiber batches. This EAP material was shown experimentally to produce close to 200% linear strain and pulling strength that is higher than human muscles [13]. To encase the fibers and chemicals that make up their EAP actuator, they designed an electrochemical cell. For the skeleton of the arm they used a structure that is made of composite material and, for support, this structure was connected to an aluminum base.

FIGURE 6: The VT students' arm wrestling with the student. Panna needed the goggles for eye protection from the chemicals that were used for their EAP material.

This contest helped in pursuing the goals of the challenge, namely:

1. Promote advances towards making EAP actuators that are superior to the performance of human muscles

2. Increase the worldwide visibility and recognition of EAP materials
3. Attract interest among potential sponsors and users
4. Lead to general public awareness since it is hoped that they will be the end users and beneficiaries in many areas including medical, commercial, etc.

Expert Opinion: Needs and Opportunities

For many years, electroactive polymers (EAP) received relatively little attention due to their limited actuation capability and the small number of available materials. In the past fifteen years, a series of new EAP materials have emerged that exhibit large displacement in response to electrical stimulation. This capability of these new materials is making EAP materials attractive as actuators for their operational similarity to biological muscles, particularly their resilience, damage tolerance, and ability to induce large actuation strains (stretching, contracting or bending). The application of these materials as actuators to drive various manipulation, mobility, and robotic devices involves multi-disciplines including materials, chemistry, electromechanics, computers, and electronics. Even though the force of actuation of existing EAP materials and their robustness require further improvement, there has already been a series of reported successes in the development of EAP-actuated mechanisms. Successful devices that have been reported include a fish-robot (described earlier), audio speakers, catheter-steering element [14], miniature manipulator and miniature gripper, active diaphragm, and dust wiper. The field of EAP has enormous potential in many application areas, and, judging from the range of inquiries that the author has received since his start in this field in 1995, it seems that almost any aspect of our lives can potentially be impacted. Some of the considered applications are still far from being practical, and it is important to tailor the requirements to the level that current materials can address. Using EAP to replace existing actuators may be a difficult challenge and therefore it is highly desirable to identify a niche application where EAP materials would not need to compete with existing technologies.

The development of an effective infrastructure for the EAP field is critical to the commercial availability of robust actuators and their use in practical applications. The challenges are enormous, but the recent trend of international cooperation, the greater visibility of the field, and the increased funding of related research offer great hope for the future of these exciting new materials. The arm-wrestling challenge of a match between an EAP-actuated robot and a human opponent highlights the potential of EAP. Progress toward overcoming this challenge will lead to great benefits to mankind. The author believes that an emergence of a niche application that addresses a critical need will significantly accelerate the transition of EAP from novelty to actuators of choice. In niche cases, these materials will be used in spite of their current limitations, taking advantage of their uniqueness.

The use of robotics contributed significantly to reduction in mortality after surgery, faster recovery and minimized complications. An example of the existing robotics is the de Vinci surgical system that is becoming a standard tool in increasing number of hospitals worldwide. Unfortunately, the current systems are quite large and do not allow for delicate surgical procedures as required, for example, in the brain. One may consider a minimally-invasive robotic arm as a surgical tool that has an octopus-configuration with multiple degrees of freedom tentacles equipped with various tools. In developing such a technology one may use beside EAP as actuators also take advantage of the capability of ElectroRheological Fluids (ERF) to become highly viscous when subjected to electrical excitation. This property can allow controlling the rigidity of flexible robotic arms and also operate as haptic interface [1 and 11]. A graphic illustration of such a futuristic concept is shown in Figure 7 and it is biologically-inspired using the octopus tentacle structure offering capabilities that are impossible today [1, 2 and 15].

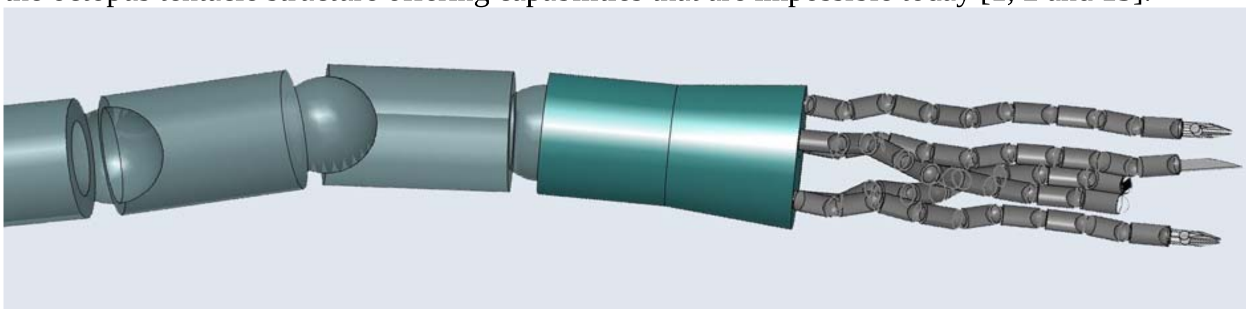

FIGURE 7: A graphic view of an octopus-configured catheter for surgical applications.

The required EAP actuators can be based on the Multifunctional Electroelastomer Roll (MER) Actuators that were developed by SRI International [16]. This actuator has a cylindrical shape and it is made of dielectric elastomers that have been demonstrated to produce 380% actuation strain. Such actuators have already exhibited high strain and moderate stress (up to 8 MPa). The response speed varies in a wide range from 1 Hz to as high as 20 kHz, depending on the type of materials and the amount of strain. One-degree-of-freedom (1-DOF), 2-DOF, and 3-DOF spring rolls have been demonstrated wherein the compliant electrodes are not patterned, are patterned on two, and are patterned on four circumferential spans, respectively.

Space applications are among the most demanding in terms of the harshness of the operating conditions, requiring a high level of robustness and durability. Making biomimetic capability using EAP material will potentially allow NASA to conduct missions in other planets using robots that emulate human operation ahead of a landing of human. For an emerging technology, the requirements and challenges associated with making hardware for space flight are very difficult to overcome. However, since such applications usually involve producing only small batches, they can provide an important avenue for introducing and experimenting with new actuators and devices. This is in contrast to commercial applications, for which issues of mass production, consumer demand and cost per unit can be critical to the transfer of technology to practical use. Some of the challenges that are facing the users of EAP materials in expanding their potential applications to space include their capability to respond at low or high temperatures. Space applications are of great need for materials that can operate down to single digit degrees of Kelvin or as high temperatures in the hundreds of Celsius as on Venus. Another challenge to EAP is the development of large scale EAP in the form of films, fibers and others. The required dimensions can be as large as several meters or kilometers and in such dimensions they can be used to produce large gossamer structures such as antennas, solar sails, and various large optical components.

In order to exploit the highest benefits from EAP, multidisciplinary international cooperative efforts need to grow further among scientists, engineers, and other experts (e.g., medical doctors, etc.). Experts in chemistry, materials science, electro-mechanics/robotics, computer science, electronics, etc., need to advance the understanding of the material behavior, as well as develop EAP materials with enhanced performance, processing techniques and applications. Effective feedback sensors and control algorithms are needed to address the unique and challenging aspects of EAP actuators. If electrically-driven artificial muscles can be implanted into a human body, this technology can make a tremendously positive impact on many human lives.

Five-years View

The field of EAP is far from mature but advances in the various elements of the field infrastructure are expected to lead to a growing number of applications in the coming years. The development of three EAP actuated robotic arms that wrestled on March 7, 2005 with the human opponent, 17-year old female student, is a major milestone for the field. Even though the student won against the three arms the competition helped increasing the visibility of the field worldwide and the recognition of its potential. The longest to hold against the student has been the arm from ERI and it lasted for 26-seconds. To get a prospective to this major milestone for the field of EAP one may want to be aware that the first flight of the Wright brothers before over hundred years lasted only 12-seconds. While there is more needed work in order to reach the level of wining against human it is inevitable that this would happen just like the check game between the champion and the Big Blue IBM computer. Initially, the challenge is to win a wrestling match against a human (any human) using a simple shape arm with minimum functionality. However, the ultimate goal is to win against the strongest human using as close as possible as resemblance of the shape and performance of the human arm. Once such a robotic arm wins against human, it would become clear that EAP performance has reached the level that devices can be designed and produced with the many physical functions of humans with superior capability. Such a success is one of the ultimate goals of the field of biomimetics.

EAP materials that produce high actuation displacement and force are opening new avenues to bioengineering in terms of medical devices for diagnosis, treatment and assistive devices for disabled. Applications that are currently being considered include catheter steering mechanism [12], vein connectors for repair after surgery [http://www.micromuscle.com/1024.htm and 17], smart prosthetics [18], Braille displays [1 and 19] and others. Recent research at the Sungkyunkwan University, Korea, has led to the development of a series of mechanisms and devices that use dielectric elastomer EAP [20]. These devices include a smart pill, which is made as a tube-like structure that performs inchworm motion for traversing thru gastrointestinal track. A flexible skin of the smart pill was fabricated using a 3-D molding technique. Using dielectric EAP, these researchers in Korea are also developing Braille display for visually impaired and it is designed to be compatible with existing Braille devices. The performance of the Braille device is currently under evaluation, where blind patients are given display patterns of letters and symbols and they are asked to recognize them. The use of dielectric elastomer EAP for Braille display has also been a subject of study at SRI [16] where a simple mechanism was constructed taking advantage of the large strains and high energy density of this EAP material.

In summary it is difficult to predict what exactly will happen in the next five years but one can assume some level of success in the current exploration of applications worldwide. This include drug release mechanisms using smart peels with a shell that shrinks or expands as needed for the controlled release, catheter steering system that allows reaching various areas of the blood system as desired, active Braille displays that can possibly used as an aid in converting video images of the street helping the blind walking independently, and possibly assistive exoskeleton devices that are biologically inspired.

Key Issues

Most conventional mechanisms are driven by actuators are requiring gears, bearings, and other complex components that are costly and prone to failure. Emulating biological muscles can enable various novel manipulation capabilities that are impossible today. Electroactive polymers (EAP) have emerged with the capability to mimic muscles to actuate biologically inspired mechanisms. EAP are resilient, fracture tolerant, noiseless actuators that can be made miniature, low mass, inexpensive and consume low power. EAP can potentially be used to construct 3-D systems, such as robotics, which can only be imagined as science fiction using such capabilities as inkjet printing. However, these materials are still limited by various challenges.

- No established database or standard test procedures
- Low actuation force, mechanical energy density and conversion efficiency
- Notch applications are needed where the specifications are within the EAP capability range
- The electronic EAP are limited by the need for quite high voltage while the ionic type is sensitive to contamination, and suffers electrolysis when subjected to voltages above 1.23V.
- Robustness – there are lifetime and reliability issues
- Scalability – it is not obvious how to make very large or very small EAP
- Competitiveness – there is a need for niche applications where it would not need to compete with existing technology.

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1. **WW-EAP Webhub:** http://eap.jpl.nasa.gov
2. **Books and proceedings** http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm
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