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Electric Flex

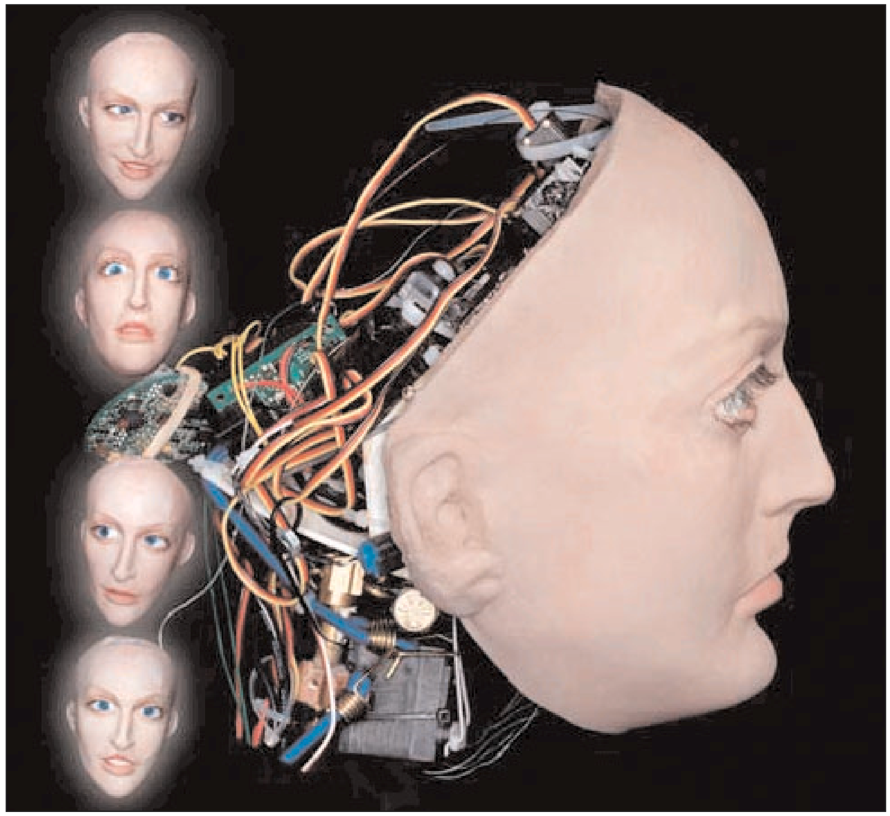
Electrically activated plastic muscles will let robots smile, arm-wrestle, and maybe even fly like bugs

BY YOSEPH BAR-COHEN

I ISSUED A CHALLENGE a few years ago to my fellow researchers: build a robot using muscles of electrically activated polymers that could arm-wrestle a human. I was trying to jump-start research in the field of electroactive polymers, or artificial muscles, and given the state of the art at the time, I didn't really expect to see the challenge fulfilled for a couple of decades.

I was wrong. A little over a year ago, researchers from SRI International, a research institute in Menlo Park, Calif., told me that their technology could be capable of meeting the challenge. Since then, Environmental Robots Inc. and the Swiss Federal Laboratories for Materials Testing and Research informed me that they would be ready to compete less than a year from now! I couldn't be more delighted—even if it means that my obligations as an impresario are a lot closer than I'd envisioned.

The arm-wrestling match, when it does come off, will be a watershed on more than one count. Today's machines—from assembly-line robots to electric toothbrushes—move thanks to rotary power, often cleverly translated by gears, pulleys, hydraulic tubes, and other intervening parts. Yet such watchmaker's cleverness has its limits, and over the centuries, engineers have imagined countless wonderful machines that sadly could not see the light of day. Now, at last, a streamlined solution is at hand: artificial muscles.



TURNING HEADS: Robotic heads like this one, designed by David Hanson, a sculptor and engineer, could one day display a full range of facial expressions, thanks to artificial muscles.

Artificial muscles are plastics that change shape and size under electrical stimulation. Because they are plastics—that is, polymers—they are light and can be cheap, pliable, quiet, and shatterproof. Also, they can be designed for particular properties, filled with sensors and other components, shaped for specific actuators, and manufactured on scales both macro and micro. Unlike most active materials, such as semiconductors and shape-memory alloys, however, these electroactive polymers work according to a variety of principles, offering different tradeoffs of power, extensibility, reaction time, and other qualities.

The list of hoped-for applications of electroactive polymers reads like an excerpt from a sci-fi writer's notepad: artificial limbs and organs, steerable endoscopic catheters, strength-amplifying exoskeletons for astronauts and disabled people, and muscles to make truly lifelike humanoid robots [see photo, "Turning Heads"]. It includes small robots that fly like insects or burrow like worms, robotic hands that transmit the sense of touch directly to the hand of an operator through virtual-reality gloves, and wall coverings that sense sound waves and generate antinoise waves to cancel them out. In fact, the first commercial applications of these polymers have already appeared, if only as toys—in

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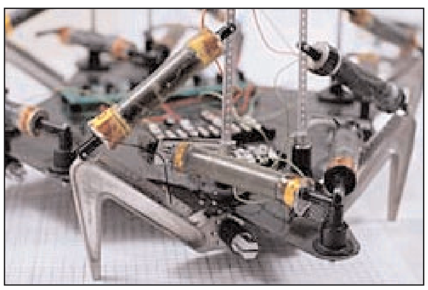

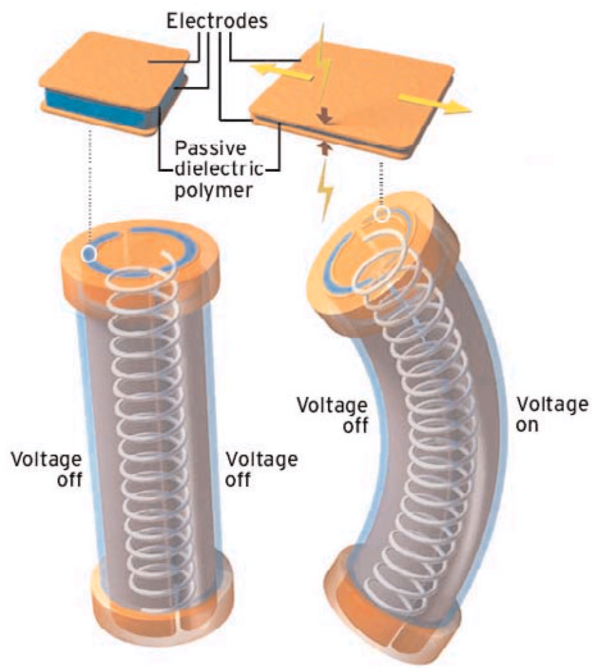

ELECTRONIC MUSCLE:
Passive dielectrics are a variant of artificial muscle activated by the movement of electrons. In an actuator, two flexible conducting plates form a sandwich [illustration, right] with the passive dielectric, a springy, insulating plastic, as a filling. When the plates are given opposite charges, their mutual attraction flattens and expands the filling.

A bending actuator, built by SRI International, Menlo Park, Calif., is made from two C-shaped strips of such an artificial muscle that surround a spring-loaded tube [above left]. When one strip is charged, it expands, bending the actuator.

SRI used multiple passive dielectric artificial muscles to build an insectlike robot called Flex [left].

December 2002, a Japanese company, Eamex Corp., in Osaka, produced robot fish that swim in an arrestingly natural way. Pulses of power from a coil in the fish tank are received by a corresponding coil in the fish. These power the toy's polymer actuators, propelling it through the water.

I entered this field, inadvertently, a decade ago. I had won a three-year contract from NASA to develop an artificial muscle based on polymer actuators described in a 1982 paper, for, among other things, amplifying the strength of an astronaut in a spacesuit. The authors claimed their actuators generated an enormous amount of force and had a whopping contractility, or strain, of almost 15 percent—meaning they could contract 15 percent of their length. After about a month working on the project, my team and I discovered that they had erred on the high side to the tune of four orders of magnitude. The hope of making a muscular spacesuit deflated before my mind's eye, and so I began a feverish search for alternatives.

I found two other electroactive polymers that had already been reported to show a significant actuation strain, and although they were not strong enough to amplify an astronaut's body movements, I was still able to develop other robotic applications, including an actuator for a miniature lens wiper. This wiper was selected for use in a tiny vehicle called Nanorover, which was to have been sent to an asteroid in 2002 in a joint Japanese-U.S. mission. Even though the mission was canceled and the wiper never got a chance to brush aside any space dust, NASA's imprimatur gave impetus to research into electroactive materials.

Meanwhile, I discovered that though several research groups around the world were already working on this subject, they scarcely communicated with one another. I therefore sent out a flurry of e-mails, cadged over 50 papers, and in 1999 held the first annual international conference in the field.

I inaugurated the conference with a challenge to develop a robotic arm powered by artificial muscles that could beat the world heavyweight champion arm-wrestler. The International Society for Optical Engineering (SPIE), in Bellingham, Wash., the society that organizes the conference each year, is seeking prize money for the competition.

The first stage in the arm-wrestling series requires that the machine beat even a weakling. This stage in the competition will take place at SPIE's Smart Structures/Non-destructive

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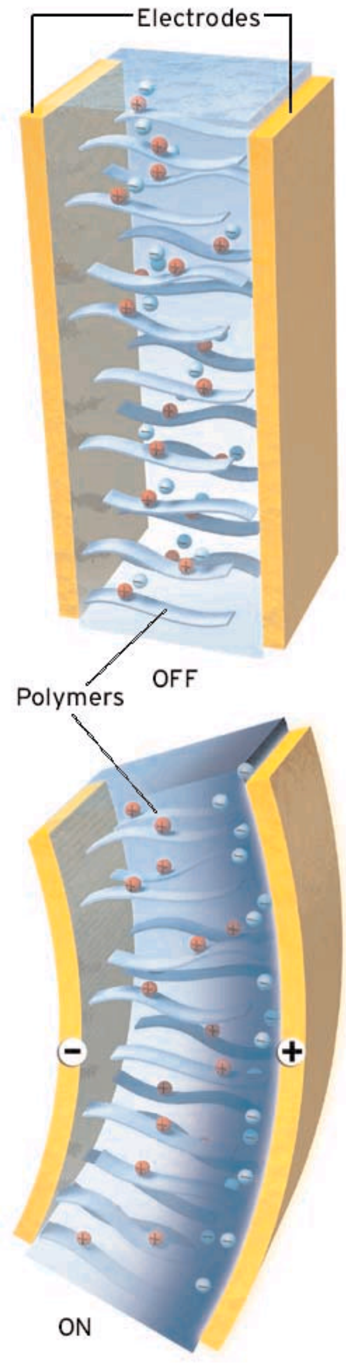
Evaluation symposium next March in San Diego. Later competitions will face ever better arm-wrestlers, using ever more humanlike mechanical designs. The ultimate goal is to have the machine arm-wrestle John Brzenk Jr., considered to be the best arm-wrestler in the history of the sport.

Real human skeletal muscles remain the touchstone of success. They achieve as much as 50 percent strain, contracting to half their length, although their force peaks at about 35 percent strain, where they can generate up to 350 kilopascals (kilonewtons per square meter). At that point they deliver their maximum power density of 150-225 watts per kilogram. Brzenk, for his part, can lift 55 kg in the one-armed dumbbell curl, an exercise that requires few of the muscles that come into play in arm-wrestling.

Beating Brzenk would be quite a technological feat. It is just the beginning, though, of a biomimetic project, in which art imitates life. Engineers would love to make machines with the abilities of an octopus, which can squeeze its body through a small hole, come out the other side, and revert to its normal shape—all without a single drive shaft, gear, or bearing.

I LIKE TO GROUP ARTIFICIAL MUSCLES into two categories, classified by their main means of activation: electronic and ionic. Electronic materials shuttle electrons about, ionic ones move ions around. Within each category are many subtypes, each with its own strengths and weaknesses. The first artificial muscle, by the way, made of natural rubber, was of the electronic kind, demonstrated by Wilhelm Konrad Röntgen 15 years before he discovered X-rays.

Because electrons move more easily than ions, the electronic polymers react in mere microseconds. They also have a greater energy density and can



IONIC MUSCLE: Ionic polymer metal composites are a form of artificial muscle that depends on the movement of ions for motion. Flexible metal foils sandwich a wet polymer filling. With the foils charged, free ions flow toward one side, expanding it and bending the actuator. The only consumer items based on artificial muscles are toy fish made by Eamex of Osaka, Japan, which use such polymer metal composites.

be operated in the open air, whereas ionic materials must be bathed in liquid solvents. The electronic polymers, however, had long required much stronger electric fields to cause them to contract—more than 150 volts per micrometer, dangerously close to the level at which these materials break down. But advances made less than a year ago have reduced the required field strength by about an order of magnitude.

Within the electronic category are five subcategories: passive dielectrics, piezoelectric polymers, graft elastomers, liquid crystals, and electrostrictive paper.

Of this group, the passive dielectrics are the simplest and also the most robust. Two conducting plates form a sandwich with a filling of springy, insulating plastic. When the plates are given opposite charges, as in a capacitor, their mutual attraction squeezes the filling, extruding it at the sides to do work [see illustration, "Electronic Muscle"]. SRI has a material that can expand by 380 percent, the record for an artificial muscle, but because the sandwich filling is very soft, the force it develops is limited.

Using a clever design and a stiffer filling, SRI managed to make an actuator that can exhibit a pressure of about 8 megapascals, which is about 30 times stronger than human muscle, gram for gram. The actuator, about the size of a finger, can bend sideways and lift a weight of about a kilogram.

Piezoelectric polymers work similarly to the more familiar piezoelectric ceramics found in inkjet printers and ultrasound transducers, by changing

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their crystalline structure—bending chemical bonds to, for instance, turn rectangles in the lattice into parallelograms. The increase or decrease in volume creates mechanical pressure. Piezoelectric polymers were discovered back in the 1920s, but because they showed a relatively small strain and force, they remained a curiosity until the development of a subclass, called ferroelectrics.

In the mid-1990s, Qiming Zhangand co-workers at Pennsylvania State University in University Park demonstrated strains in their ferroelectric polymers of 4 percent—not a lot, but it comes with a lot of force: about a gigapascal. But Zhang's technology is not quite ideal, in part because it needs high voltages to deliver muscle-like power and energy.

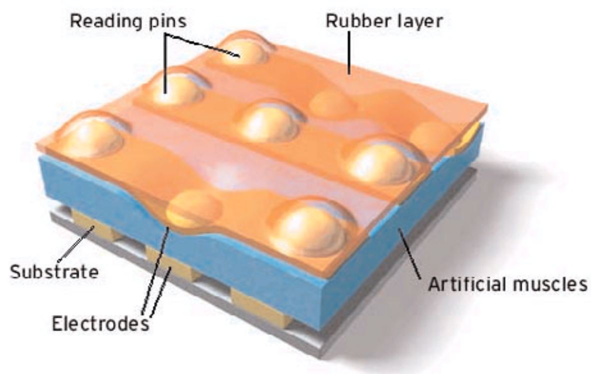
In the graft elastomer, a long backbone molecule is engrafted with elements that respond to an electric field. A rather high voltage contracts the entire structure. One such material, developed by Ji Su at NASA Langley, in Hampton, Va., produced a strain of about 4 percent and a rather strong force.

Liquid-crystal muscles work by undergoing a sudden phase change from an ordered crystalline phase to a disordered soup when electrically heated through the phase transition temperature. Groups, particularly teams in the U.S. Navy and in Germany, have been reporting great forces, as well as greater stretch than that found, say, in ferroelectrics. But the need to heat and cool the muscles makes them slow to respond and inefficient.

Electrostrictive paper is a type of artificial muscle discovered serendipitously by Jaehwan Kim at Inha University, in Inchon, South Korea, who began his experiments, essentially, with cellophane tape. Glue two layers of silvered tape together and, surprisingly, the end product will shrink when charged. After varying the numbers of layers and the materials in the electrodes and adhesives, he found a reasonable, and very cheap, technology for large-area applications. One idea people have for using electrostrictive paper is to make an electronically active form of acoustic tile. The tile would broadcast anti-noise to cancel out sound in a room.

JUST AS VARIOUS AN ASSORTMENT of ionic muscles exists. In general, the ionics are less energy efficient—less than 30 percent, even under the best conditions, compared with the 80 percent seen in some of the electronic muscles. But they have the advantage in at least two respects: they react to drive voltages as low as 1-5 volts, compared with the electronics' tens of volts per micrometer of thickness. Even better, they readily produce bending motions, rather than just expanding or contracting.

Polymer gels—materials formed of chainlike molecules dissolved in a solvent to form a semisolid—have been investigated for years as sensing devices as well as actuators. Chemical stimulation is possible—changing the acidity of the surrounding liquid can, for instance, cause a movement of ions into or out of the gel, forcing it to contract or expand. But electrical stimulation can produce the same effect and is more convenient for most machine designs. Environmental Robots in Albuquerque, N.M., plans to use this type of polymer to drive its wrestling robot.



RUBBER READER: Researchers in several countries are developing a device to allow blind people to read text in a computer display. The Braille reader uses a filling of artificial muscle beneath an array of bumps on a separate pad on the keyboard. Polarizing the electrodes beneath each bump contracts the muscle and pulls the bump below the pad's surface, to create Braille characters.

Polymer metal composites, developed independently by Keisuke Oguro, Keya Sadeghipour, and Mohsen Shahinpoor, shuttle ions from one side of a band of muscle to the other, causing contraction on one side and expansion on the other [see illustration, "Ionic Muscle"]. The resulting bending can be reversed easily and lends itself to movements that engineers have, in the past, achieved only by Rube Goldberg-type heroics. The Japanese toy fish, mentioned earlier, are driven by this device; so is the front end of a catheter, developed in Osaka, that steers itself through the circulatory system.

Conductive polymers achieve the same sort of complementary stresses by another means. If two conductive polymer films are separated by a polymer electrolyte and are independently connected—one as a working electrode and the other one as a counterelectrode—one of the conductive films will

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expand and the other one will contract. In general, the one expanding will be the one ions are entering, and the one contracting will be the one ions are exiting.

Carbon nanotubes, the darlings of nanotechnology research, are a work in progress, more promising for their potentially spectacular results than for any achievements so far. These tubes, chemical cousins to the famous buckminsterfullerene molecule—a soccer-ball-shaped cage of 60 carbon atoms—show the highest tensile strength known. Theoretically, they are some 100 times as strong as an equivalent mass of steel, and they also survive at temperatures up to 1000 oC. Electric charging causes ions to attach to the carbon cage, shortening the carbon-carbon bond lengths and creating strains of 1 percent—not very much, but potentially very powerful.

Electrorheological liquids change their viscosity dramatically when an electric field aligns suspended particles, setting up a logjam of material. The effect can create a virtual valve, throttling the flow of fluid between the electrodes. Unlike most ionic systems, this one is quick off the mark, reacting in as little as a 10th of a second.

IN PRACTICE, IF NOT THEORY, all these artificial muscles are rather weak and inefficient. Nobody is going to use them to punch sheet metal into industrial dies or to drive home rivets. Moreover, they are not standardized yet and therefore are difficult to incorporate into mass-produced devices, a problem stemming from the very richness of choice that the field enjoys. No one actuator class has gained an ascendancy that would grant it the lion's share of R&D investment.

Finally, some of the materials tend to exhibit short working lifetimes, breaking down from material fatigue or electrochemical forces. To find a use beyond toy fish, the actuators must become tough enough to last through millions of cycles.

For the present, we must keep on playing with the materials, pinning down their characteristics, optimizing them for particular functions, and making them with the consistency that manufacturers demand. It is a multidisciplinary undertaking, combining the insights of computational chemistry, materials science, electromechanical models, and processing techniques. The goal is to produce not merely better actuators, but also a database of their pros and cons, so that designers in every field can choose options from a list, without having to reinvent the wheel, as it were.

The part of the job that ought to come first will, in the nature of things, come last: the discovery of the proper applications. A new technology doesn't usually take over a niche by displacing an established one, at least not at first. Rather, it does something valuable that existing methods cannot do at all. The steerable catheter and even the toy fish are examples of this. So is an active Braille display for reading computer screens, which I conceived, that is now under development at several universities [see illustration, "Rubber Reader"].

In thinking up jobs that only artificial muscles can do, designers should keep in mind certain peculiarities that most of those muscles share. A normal muscle must expend energy to maintain a constant degree of strain, as in an isometric exercise like holding a book out away from one's body. However, artificial muscles, particularly the electronic type, expend energy only when moving from point to point; maintaining a static position takes no effort at all. Also, one can change the electrical properties of polymers by impregnating them with other chemicals just as one does with semiconducting crystals, to produce materials that are even more closely tailored to the needs of the job at hand.

In any case, the early applications will emphasize unique performance rather than cost and therefore will perhaps come first in space-based systems. In my lab at the **Jet Propulsion Laboratory**, in Pasadena, Calif., we have been working on a number of devices. These include a wiper to remove dust from the windows and solar cells of spacecraft, large membranes that could unfold from a compact container to produce gossamer-thin structures, and a miniature gripper that can lift objects much as a human hand and fingers do. The gossamer membrane may even find an application in consumer electronics: SRI has developed a polymer membrane to serve as the active element in a thin, lightweight speaker.

Perhaps the greatest application will be in tiny devices. Some of these may even be manufactured by stereolithography, in which an inkjet nozzle sprays minuscule drops of polymer onto other materials to form layered, three-dimensional structures. You can imagine using such means to build an entire, insectlike flying robot from the ground up—plastic microelectromechanical systems (MEMS) engineering.

Living systems are the test case, the challenge that gets researchers' juices flowing, in part because the animation of animal-like models has been so enormously difficult. Think of the ingenuity that engineers had to show to get a model of Abraham Lincoln to stand up, gesture, and deliver the Gettysburg Address to onlookers at Disneyland. Solve this general problem of movement, and surely a great range of possibilities will arise.

Not long ago, I asked the engineer and sculptor David Hanson to build a test bed for artificial muscles: an android head that can make a few

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facial expressions. Right now it is operated in the familiar animatronic kludge by conventional electric motors. But I look forward to the day when effective artificial muscles can be incorporated into the skin of an android, allowing it to master the full range of human expression.

You might argue that machines need not accomplish their set tasks exactly as humans or animals do them—nobody, for instance, would want to fly in an airliner with flapping wings and feathers. But I and many robotics researchers firmly believe that we can learn much from emulating nature, and that a smiling android, an arm-wrestling robot, and a polymer-powered butterfly will turn out to be far more useful for what they suggest than for what they do.

TO PROBE FURTHER

For more information on artificial muscles, read Electroactive Polymer Actuators as Artificial Muscles (SPIE Press, Bellingham, Wash., 2001), edited by Yoseph Bar-Cohen.

The author's Web site, http://eap.jpl.nasa.gov, contains links, videos clips, and information about the arm-wrestling contest and the artificial muscle industry.

The Web sites for the three arm-wrestling contestants so far are:

SRI International, http://www.esd.sri.com/automation/actuators.html; Environmental Robots, http://www.environmental-robots.com/; and Swiss Federal Laboratories for Materials Testing and Research, http://www.empa.ch.