Dan Ferber

Will Artificial Muscle Make You Stronger?

The world's first human-robot arm-wrestling match shows off the potential of a new material that someday could power machines—and even human limbs and organs.

In the annals of organized arm wrestling, there had never been a match like this. Ever since 1952, when the first official arm-wrestling competition took place at Gilardi's Saloon in Petaluma, California, contestants have generally been large men with unusually muscular forearms. But on this Monday afternoon, the TV cameras focus on a slim 17-year-old girl. Panna Felsen's very participation is odd for a sport that still counts events like the Bad-to-the-Bone Armwrestling Championship in its lineup (and the fact is, she trained harder for her high school's Science Olympiad than for today's event). But even more unusual is her opponent. As match time approaches and the crowd grows quiet in the cavernous hotel ballroom, Felsen glances shyly at the phalanx of journalists surrounding her. Then she walks to the padded regulation arm-wrestling table, places her elbow down, and grips her opponent—a white plastic robotic arm.

The first-ever human-robot arm-wrestling match, held in March in San Diego, marked a milestone—as the emcee, Yoseph Bar-Cohen, a physicist at the Jet Propulsion Laboratory in Pasadena, was eager to declare to anyone within earshot. Never mind that Felsen's opponent looked more like a beefed-up bowling pin than a real human arm. What mattered was the way it moved. The arm that Felsen was about to wrestle, and two more waiting in the wings, had no gears, no shafts, no cams, no moving metal parts whatsoever—a fact that distinguished them from windshield wipers, disk drives, prosthetic limbs, and the millions of machines on Earth that create motion using electric motors. The robotic arm clamped to the table across from Felsen was propelled entirely by plastic.

The material driving these arms is a little-known one called electroactive polymer that has an unusual property: When stimulated by electricity or chemicals, it moves. It expands and contracts, curls and waves, pushes and pulls. It's also springy, durable, quick, forceful, and quiet. Since those properties are shared by human skeletal muscles, electroactive polymers have been dubbed "artificial muscle."

Artificial-muscle enthusiasts like Bar-Cohen foresee a vast array of cheap, light, versatile, and powerful actuators—motion-generating devices—for military technology, space vehicles, and medical devices. Roy Kornbluh of SRI International, a pioneering artificial-muscle researcher, predicts that the materials could ultimately replace up to half the planet's 1 billion electric motors. Already engineers are developing artificial-muscle-powered devices, including a knee brace that prevents injuries; tiny pumps to deliver drugs; and robots that wriggle like snakes, fly like birds, or hop like grasshoppers.

But beyond those devices lies an even more ambitious goal: to replace the genuine article. "In this material, we have the closest to real muscles we ever had," Bar-Cohen says. Research has begun on a variety of medical devices that would be implanted in or attached to people's bodies, such as artificial-muscle-powered prosthetics, a pumping device to assist diseased hearts, a urinary sphincter to treat incontinence, and an artificial diaphragm to help people breathe. Further—much further—down the road, scientists talk of plastics that could replace or augment any muscle in the body.

Six years ago, Bar-Cohen issued a challenge: Build a robotic human arm that could beat the strongest arm wrestler on Earth. But by 2003, impatient to see his contest actually happen, he eased the requirements. It would be necessary only to prevail over a high-school student, he announced. The rules: Robot arms "should not perform any irritating acts," such as flashing blinding lights, vibrating, or making annoying noises. And to win, the robot arm would have to be able to rotate back to its starting position after pinning the human. Now, at the annual scientific conference on artificial muscle in San Diego, three teams claim to have made such a device. The upcoming event excites Bar-Cohen no end. "It's incredible that we have it at that level!" he raves.

So at just after 5 p.m., Felsen, a senior at nearby La Costa Canyon High School, faces her first opponent. (Bar-Cohen chose her after learning that she'd started an engineering club at her high school and liked to build simple robots for fun.) Projected on a two-story screen at the front of the ballroom is an image of the robotic arm and Felsen, who at the moment resembles a deer in the headlights. Bar-Cohen quiets the crowd in his thick Israeli accent. "OK, go!" he barks. An arm-wrestling champion who had come to see the match has volunteered to help Felsen with her technique. He crouches by the corner of the table. "Stay close. Up on your toes," he says. The robot doesn't budge. Felsen, straining, manages a self-conscious smile. "Push harder!" her coach urges. Felsen's face grows determined, and she struggles to tip the robot arm over.

Ask a bioengineer about muscle, and you'll hear high praise and a spec sheet full of properties. First and foremost is force. A thigh muscle can generate 36 pounds of force per square inch—enough to snap a pine board. Then there's power, the rate at which the force is applied over distance. As in automobiles, high power leads to tremendous speeds; a typical skeletal muscle produces horsepower that pound for pound is "way more than a car engine," says bioengineer Richard L. Lieber of the University of California at San Diego. Muscles also act as brakes, springs, and shock absorbers, which is why we, unlike your typical robot, can run, jump, and land softly. And finally, as a waggish British biologist once put it to a roomful of engineers, muscle is "good to eat."

Artificial muscle will never rival a good rib eye, but it's on its way to replicating many of muscle's other properties. To generate force on command, a material must first be able to deform, like a rubber band, at the flick of a switch. It must contract or expand far enough to move an object a sufficient distance. And it must be stiff enough to generate sufficient force. An effective arm-wrestling robot has to match the force of human torso muscles while rotating an armlike extension and must have sufficient control to adjust its force as necessary. "It's the ultimate in application," Bar-Cohen says. "If I can do that, I can make something useful." The three arms pitted against Felsen each employ a different type of artificial muscle, so the contest will double as a test of the field's most promising technologies.

Felsen's first opponent was built by Mohsen Shahinpoor at Environmental Robots, a small Albuquerque-based company. It's made of ionic polymer metal composites (IPMCs), which require low voltages but move rather slowly. IPMCs are bendable, and so they can be molded into whatever sort of actuator will be most powerful.

If a bookie were laying odds on this match, the favorite would probably be Felsen's second opponent, built by a team of Swiss government engineers. This arm is propelled by dielectric elastomers, films in which thin carbon-based electrodes sandwich a soft plastic such as silicone or acrylic. Electricity draws the electrodes together, squeezing the plastic, which expands to up to three times its normal area in about half a second. Actuators made of dielectric elastomers exert up to 30 times as much force, gram for gram, as human muscle. But they require several thousand volts of electricity—a bit of a problem if you want to use them near, or in, the body.

Felsen's third opponent is the underdog. A team of undergraduates from Virginia Tech University, working long nights on a tight budget, created a gel fiber that shrinks when acid is added. The students couldn't get anyone to donate the artificial muscle, so they made it themselves. Their creation is slow to get going but contracts a lot, up to 40 percent of its length, and has the additional benefit of requiring no electricity.

All three teams arrived early to prepare. As the hours tick down, the pressure mounts.

At the resort where the artificial-muscle conference is being held, palm trees lean over red brick walkways and relaxed tourists mill around in colorful beach clothes. Inside a low-slung building, it's easy to spot the Swiss team—they're the anxious-looking engineers talking together in low murmurs. Their device sits on the floor of a conference room. It's a black fiberglass-composite box.

Gabor Kovacs, the team's lead engineer, has been building dielectric elastomers for five years. His goal is to develop shape-shifting actuators that could be used, among other things, to reduce wind resistance in blimps. But lab tests on the material only go so far; last year he took up the arm-wrestling challenge. “We wanted to see the possibilities and limits of this technology,” he says.

After consulting biomechanics texts, Kovacs and his team, who work for a government lab, decided to simulate the torso muscles an arm wrestler uses by rotating the entire robot (the black box) around an axle (a stand-in for the shoulder joint) while holding the “arm” stiff. To make their actuators, they built a machine that stretches a sheet of silicone and sprays it on both sides with a chemical coating. The machine then wraps this three-layer film, a dielectric elastomer, around a springy steel core. To maximize the actuators’ power, the team spent months experimenting with various chemical formulations of the coating.

This afternoon, a day before the match, Kovacs expounds on his masterpiece. It took a year to build, he tells me, and cost $250,000 in Swiss government funds. It possesses 256 actuators, powered by up to 4,000 volts. But before he can finish, two young men appear. They confer in German, glancing unsmilingly at the arm ’bot. As they pick it up and prepare to leave, the only words I understand are “Home Depot.”

The designer of the beefed-up bowling pin, Felsen’s first opponent, sits across a table from me in the hotel ballroom and grips my hand in an arm-wrestling posture. Mohsen Shahinpoor runs the Artificial Muscle Research Institute at the University of New Mexico and directs research at Environmental Robots. In a technical talk that day, he had shown videos of his devices in action. In one, a human skeleton pedaled a bicycle, powered by strips of artificial muscle.

Shahinpoor tightens his grip and tells me to push. As I start to win, he pushes back forcefully. His robot arm is programmed similarly: to add power when it starts losing. A sensor measures the angle between the arm and the table and increases voltage as needed.

Shahinpoor's IPMCs consist of two metal-foil electrodes sandwiching a wet, Teflon-like plastic soaked with lithium ions. Just 12 volts—the equivalent of a car battery—cause the lithium ions, which are positively charged, to migrate toward the negatively charged foil layer, bulking up that side of the actuator and bending the IPMC. IPMCs are safer than dielectric elastomers because they use low voltages, and they're stiffer, which enables them to exert more force per actuator. But they're more sluggish because they're triggered by bulky ions, not speedy electrons.

Environmental Robots spent $24,000 to develop the arm (more if you count Shahinpoor's time). He tells me that he limited the machine's voltage and force; he's more concerned about demonstrating its potential, and about the human contestant's safety, than about winning. When we finish talking, he heads to the event. Soon Felsen is pushing against his 'bot as a bemused crowd of about 150 looks on. She is using her arm, not her whole body, and she's struggling. "Push harder!" exhorts the arm-wrestling champ. Twenty-six seconds into the match, she pins the robot arm. She flashes a big smile as the audience applauds. Now there are two teams left.

Three clean-cut engineering students from Virginia Tech—Steve Deso, Stephen Ros, and Noah Papas—worked evenings and weekends in the lab for months to build their robotic arm as part of a project required to graduate. "We wasted our entire senior year—no partying," Deso says, and the others laugh. They spent three years in class learning about Newtonian mechanics, solid mechanics, and biomechanics and hanging out together in their spare time. "We were looking for something that would apply our skills," Ros says. They spotted an online article about the contest and joked about entering. It seemed too big a project at first, Deso recalls. They e-mailed Bar-Cohen. "He said, 'Just go for it,'" and they did.

The three decided to use an artificial muscle called polyacrylonitrile, a gel imbued with fibers for strength. After burning through their $800 budget, they begged, pleaded, and scrounged parts and help. Unable to afford polyacrylonitrile, they synthesized it, starting with textile fibers donated by the manufacturer, Mitsubishi Rayon. A prosthetics company donated a metal elbow for the arm, and a body shop spray-painted it for no cost in maroon and orange, their school colors.

Papas pulls one of their muscles from a plastic bag to show me. It's about a foot long and three-quarters of an inch thick, brown and moist; it feels like a piece of raw meat and resembles a giant slug. For the match, they'll place it inside Plexiglas and use a windshield-wiper pump to spray acid on it. They'll tie the ends of the muscle to the arm with 50-pound-test fishing line so that it can wrestle. If all goes well, the acid will penetrate the gel, neutralizing charged groups in the plastic and forcing the material to contract. The students know their muscle is strong enough to perform, but they haven't had time to test their final configuration. When the match is over, they're heading to Vegas.

The Swiss engineers clamp their arm to the table. They connect red and black leads from the box to a bank of power sources, and Felsen dons a heavy rubber glove for safety.

Bar-Cohen walks to the table, microphone in hand, and booms, “It doesn’t look like an arm, it doesn’t feel like an arm, but it is an arm!” On three, the black box emits a low hum and the scent of burning rubber. Taking pointers from the champ, Felsen uses her body this time—and downs the arm in four seconds. The audience laughs. The Swiss team, which hadn’t had the chance to fully test their creation, looks on, stone faced. “I thought we couldn’t lose,” Kessler would later tell me.

Now it’s the Virginia Tech team’s turn. The students, dressed in crisp-looking maroon polo shirts, clamp their project to the table. “Now it gets exciting,” Bar-Cohen booms. He hands the microphone to Deso, who tells the crowd how they’re going to activate their device by adding acid. Felsen dons safety goggles and grips the hand. She pushes, and in three seconds the arm flops to the table without even a hint of resistance. A few moments afterward, inside the Plexiglas contraption, the sluglike artificial muscle begins to contract. “Our goal was just to get here,” Deso tells me. “That was a huge accomplishment.” And they do seem happy. Only Ros voices a regret—that they didn’t activate their muscle earlier: “If [the match] had started five seconds later, we could have put up a fight.”

The first-ever human-robot arm-wrestling match seemed to mark an ignominious defeat for the robots. A girl who describes herself as “not very strong” had trounced some of the best artificial muscles that engineers have to offer.

But the researchers continue undaunted. Kovacs is back to making dielectric elastomer sheets that curve into complex shapes on command. Such a material could enable aircraft wings to change shape in flight or could emulate the undulating fins of a stingray to propel underwater vehicles. And Shahinpoor’s company is developing two medical devices: an adjustable band that would correct nearsightedness by squeezing the eyeball to alter its curvature and length and a device that would help ailing hearts pump blood.

Just before I leave, I spy the Swiss engineers in the exhibit hall. They have taken apart their robot and clamped one of its actuator banks to a table. Two carboys, heavy with gallons of water, hang from the actuator bank. A sign with large red letters reads, "Caution! High voltage!" With an air of mild disappointment, Kovacs explains that the rule requiring the arm to spring back prevented them from demonstrating their machine's full strength. To simulate human muscles, which operate in pairs, one contracting while the other relaxes, the team had aligned their actuators to work in opposition, canceling each other out—except for a small differential, which represented the arm 'bot's force. But now, released from the machine, their actuators could show their true power. One of Kovacs's colleagues flips a switch, and the artificial muscle hoists and lowers the carboys—up and down, up and down.

"We didn't win," Bar-Cohen acknowledges. He adds: "Twenty-six seconds is maybe nothing." Then, his voice rising with excitement, he continues, "But the first flight was 12 seconds. We have to remember that. A hundred years from now, who knows where we could be?"