In May of 2004, a twenty-three-year-old former Marine named Claudia Mitchell went for a ride on the back of a friend’s motorcycle along State Highway 71, in western Arkansas, near where she had grown up. Soon they were going faster than she was comfortable with, and she remembers feeling more alarmed than she had felt during the ferocious sandstorms she endured in Kuwait, when she couldn’t see her fingers. As she and her friend approached Mountainburg, she says, they took a sharp curve at high speed. The bike spun out of control. Mitchell was thrown, hit a guardrail, and came to rest, on her back, in a thicket. Her friend was unconscious. Mitchell felt extreme pain in her abdomen. (She later learned that her spleen had burst.) Volunteers from the local Fire Department arrived, and when an emergency medical technician found her she was desperately trying to extricate herself from the thicket.

“I kept saying, ‘My arm isn’t working! My arm isn’t working!’” Mitchell recalled recently. “I was trying to push—it wasn’t doing anything.” Her arm—her left arm—wasn’t working because it was over by the guardrail. It had been severed, just below the shoulder, on impact, although her brain continued to send signals to the primary motor nerves—the median, the ulnar, the radial, the musculocutaneous—that activate the muscles in the arm and hand. “I didn’t understand why everybody kept saying there was something so seriously wrong,” she went on. “I was in pain, but I didn’t see any blood. The E.M.T. said, ‘Yeah, honey, it’s gone, but we found it.’” He put the arm in an ice chest and brought it to the hospital.

Mitchell spent the next three days heavily sedated. (Her friend had sustained major injuries and was unconscious for weeks.) When she regained full consciousness, she learned that her doctors had decided against reattaching the arm, for fear of infection. As her recovery progressed, she resolved to learn to live with the loss of limb, but her involuntary nervous system resisted. A week after leaving the hospital, while crawling underneath a desk to get at some computer cables, Mitchell reached out to grab one with her right arm. But it was her only load-bearing arm, and she fell hard into the wall, stump first. The next three months were filled with similar mishaps. “I was constantly falling on my shoulder or reaching for things with my little shoulder, and it wasn’t going anywhere,” she said.

In “Moby-Dick,” Ahab complains of lingering pain in his missing leg, almost like a ghost, and the ship’s carpenter remarks, “Yes, I have heard something curious on that score, sir; how that a dismayed man never entirely loses the feeling of his old spar, but it will be still pricking him at times.” Mitchell, too, felt that somehow her arm was not so much gone as merely invisible—a phenomenon known as phantom limb. (Lord Nelson, having lost his right arm to cannon fire in 1797, considered his phantom fingers to be proof of the existence of a soul.) When Mitchell was fitted with a mechanical prosthesis, she tended to keep it bent at a ninety-degree angle, as though in a sling, giving visual representation to the posture of her throbbing phantom, which she was powerless to move.

Mitchell’s prosthesis was a state-of-the-art battery-powered robotic arm that operated myoelectrically; that is, by using electrodes to amplify the electrical charges from muscle contractions and drive a motorized elbow or hand. It was heavy, however, and she found it slow, and cumbersome—nearly useless. Before long, she stopped wearing it, and learned to tie her shoes and to type using one hand. She got by. Her friends called her the Queen of Backspace.

The next generation of bionic prostheses.

BY BEN MCGRATH
nessed to leather sockets, were controlled by straps running through a system of eyelets and pulleys that fit around the shoulder and back. The engineering was far from efficient, and these systems suffered from high frictional losses.

The inventor Frank Bowden, who founded the Raleigh Bicycle Company in 1888, took the arrangement to the next step. While playing around with alternatives to backpedalling as a means of slowing down, he devised hand brakes that transmitted force to the wheel rims through a set of stainless-steel wires sheathed in hollow tubes. These Bowden cables, as they are called today, offered the advantage of graduated feedback, affording riders greater control over their speed. Bowden cables were subsequently used in early airplanes, for controlling wing flaps, where such feedback is crucial. After the Second World War, Northrop Corporation, the aviation pioneer, put its aeronautical engineers to work on prosthetics and became an early builder of cable-operated arm systems. Cables replaced leather straps, and could be used reasonably well to manipulate split hooks, which provide a crude sort of opposable thumb.

Around the same time, in Munich, a physicist named Reinhold Reiter discovered myoelectric control, and, using vacuum tubes for amplification, created a stationary prototype electric hand that could be opened and closed through contractions of the residual muscles. In the late nineteen-fifties, shortly after the launching of Sputnik, Soviet scientists successfully applied myoelectricity to the operation of a portable hand, which they introduced at the 1958 World Expo, in Brussels. But progress on the merger of man with machine has been slow, and modern myoelectric devices aren’t really any better than the cable-and-pulley system. At the Walter Reed Army Medical Center, many amputees still opt for a cosmetic device—a nice, silicone hand glove, for example, attached to an aluminum shell of an arm—that has no functional capability.

Since the campaigns in Afghanistan and Iraq began, more than six hundred soldiers have returned home without arms or legs, thanks, in part, to modern body armor, which saves lives that would in earlier wars have been lost. Through the Defense Advanced Research Projects Agency, or darpa, the Pentagon is funding an initiative called Revolutionizing Prosthetics, whose goal is to produce fully humanlike replacement arms. Fifty million dollars is to be spent on complementary research teams from the academy, led by Johns Hopkins, and the private sector—DEKA Research, founded by Dean Kamen, the inventor of the Segway.

“Right now, we’ve got a hook that opens and closes,” Colonel Georey Ling, a military neurologist who is overseeing the project, said recently. “That allows you to pick up a pencil, but it doesn’t allow you to write. You can pick up a fork, but it doesn’t allow you to feed yourself.” DEKA hopes to unveil an eight-pound mechanical arm—which is lighter than a human arm—before the end of the year, and in April the Johns Hopkins researchers produced Proto 1, which offers the advantage, among other things, of swinging freely at the shoulder and the elbow, thereby allowing for more natural walking. DARPA’s plan is to have amputee soldiers not only eating, writing, and walking comfortably

We’ve rewired Claudia,” Mitchell’s doctor says. Photograph by Martin Schoeller.
mand. And I listen to you—that's my sensory coming back through the phone cable. Let's say your phone breaks, or you have an amputation. My voice is still going to that cable, and if it was hooked up to something you'd be able to hear it."

Conventional myoelectric technology ignores the disconnected nerves and attempts to harness healthy but remote muscle signals (in the shoulder stump, say, or in the back) to power computerized stand-ins for a missing elbow or hand. For the amputee, this means learning a new, much clumsier language of movement, like Morse code as a substitute for direct speech: making a fist may now require the deliberate, if counterintuitive, contraction of one's upper deltoid, and bending an elbow may involve a sequence of shrugging motions in the shoulder and neck. The burden is cognitive rather than physical, but the system is hardly more efficient than leather straps and pulleys.

If the brain can persist in thinking, on some level, that it still has a left arm to push off with, Kuiken reasons, why not give those thoughts a muscle to flex? Any muscle ought to do, as long as you can program a computer to articulate its contractions. "It's like if you go and buy a new computer to articulate its contractions. It's like if you go and buy a new phone and plug it into the old cord, and call me up," he says. "We can talk again, and I don't know you have a new phone."

As a teen-ager in the nineteen-seventies, Kuiken was a self-described gearhead and a science-fiction fan who watched "The Six Million Dollar Man" on TV. For years, Kuiken experimented with nerve transfers on rats, but it wasn't until 2002 that he got his first chance to put his idea into practice with a human. That winter, he operated on Jesse Sullivan, a fifty-five-year-old power-company technician who had lost both arms after touching a live wire. Gregory Dumanian, a surgeon on Kuiken's team, rerouted the ulnar, radial, and musculocutaneous nerves from Sullivan's left-shoulder stump to his pectoral muscle, which he then carved into four smaller pieces, one for each nerve. (The pectoral muscle was of no use to Sullivan in its original form, because he lacked arms.) With the brain-muscle connection reestablished, Sullivan was eventually able to operate a myoelectric prosthesis using nothing other than intuition. Just thinking about bending his left elbow activated the mechanical elbow socket. In a video, shot six months after the procedure, Sullivan can be seen moving his extended left arm from side to side and saying, "Wax on, wax off," in imitation of the Karate Kid. (For the right arm, he continues to use a cable and a hook.)

In the fall of 2004, a friend of Claudia Mitchell's saw a brief mention of Sullivan's success story in Popular Science. The following spring, Mitchell got in touch with Kuiken, and that August he and his team at the Rehabilitation Institute performed a similar procedure on her. In addition, they severed the existing sensory nerves in a small patch of her chest, creating a numb spot roughly four inches wide above the left breast. The relocated arm nerves then grew into this numbed patch of surface skin, reinnervating it. The results were revealed last September at a press conference in Washington, D.C., where the assembled science reporters proclaimed Mitchell the world's first "bionic woman." On a makeshift stage, she and Jesse Sullivan exchanged intuitive robotic high fives.

Not every stunt went according to plan: Mitchell dropped a bottle of water as she tried to raise it to her lips. I met Mitchell and Kuiken in New York five months later, and she said that it took her a half hour just to figure out how to tie her shoes with two hands again, but that, once she recalled the proper order of operations, she was able to do it without great difficulty. "We rewired Claudia," Kuiken explained. "We're rewiring a human to work with a machine."

Mitchell, who is small and unassuming and has long dark hair, was wearing a loose-fitting pink sweater and kept her arms folded across her lap, her right hand gently squeezing her left. The nails had been painted identically on both hands, and she wore a bracelet and a pinkie ring on her left—which, on closer inspection, turned out to be rubber (concealing metal). Her posture was awkwardly stiff, and her left shoulder appeared broader than her right, because of the harness required to hold the prosthesis in place. At Kuiken's suggestion, she opened and closed both hands, simultaneously, and then began recoiling her arms at the elbows, as if she were lifting barbells.

Kuiken is one of the scientists involved with the Revolutionizing Prosthetics project, but Mitchell's prosthesis, he explained, was not a futuristic DARPA special; it was a commercially available model that cost sixty thousand dollars, and its limitations soon became evident. It can lift only ten pounds. Two of its motors (the hand and the elbow) operated via "thought control," as Kuiken calls it, while a third, a wrist rotator, required Mitchell to manipulate a small switch near her shoulder. The motors, moreover, were noisy, and the degree of freedom in her arm was essentially confined to three types of movement. She could open and close her hand, she could flex and extend her elbow—and she could do these simultaneously, rather than sequentially, as most amputees are forced to do—but little else was possible. Kuiken named a series of more specialized hand movements—fine pinch, trigger, key grip, three-jaw chuck, power grasp—which he hoped to teach Mitchell in the coming months. She demonstrated each using her human hand. For the three-jaw chuck, this meant employing the thumb, fore-finger, and middle finger in the manner of a vending-machine claw used to retrieve stuffed animals.

In the interest of increasing Mitchell's freedom of movement, Kuiken has developed a prototype of what he calls a "six-motor arm," which he keeps at his lab in Chicago. He assembled it in patchwork fashion, like a Sunday garage mechanic, using existing components gathered from around the world. It is composed of a "Boston digital elbow" (long the industry standard), a Scottish-made shoulder, a German wrist rotator, a Chinese hand-and-wrist flexor, and a humeral rotator that was made in-house, by Richard Weir, a colleague at Northwestern. "We're like the Wright brothers here," Kuiken said. "This is the first time it's flown, but we're already getting to that biplane."
When Mitchell showers, the water hitting the patch of reinervated skin on her chest makes her feel as though her nonexistent left arm were getting wet. “When we wake the sensation in the arm back up, it’s not a question of ‘what I used to call my arm,’” Paul Marasco, a postdoctoral fellow at the Rehabilitation Institute, said in April. “It’s, like, ‘My arm’s back.’” It simply lives in her chest now.

Marasco was looking at a peculiar sort of anatomical map, which showed Mitchell’s chest. The map had been made, in the manner of all the early explorers’ maps, by trial and error—pushing on Mitchell’s chest with Q-tips, asking what she felt, and recording her description. It showed, within the chest, an array of hands, each shaded to indicate a more localized area of the palm or of specific fingers. A simplified diagram showed her over—all hand region—the original numb spot—laid out in a seventy—two-point grid, with her pinkie, for example, primarily occupying a portion of the lower right—hand quadrant, and her thumb just left of center.

Mitchell had deposited her prosthesis on a shelf that served as a kind of parking garage for artificial limbs (hers was identifiable by the jewelry), and removed her shirt, a light—green button—down tied off at the sleeve, in favor of what she called a toga. Marasco presented her with a perforated thermoplastic casing that fit snugly over her shoulder and chest. In addition to the perforations, which represented the seventy—two grid points, the exterior of the casing had been marked in a couple of places to indicate a scar and a mole on Mitchell’s skin. Marasco aligned the markings with the actual blemishes underneath, and then, using a Sharpie, made a dot on her chest through hole No. 21, which, according to the map, represented a sensation of compression on the inside edge of her thumb and the outside edge of her index finger.

Mitchell settled into a reclining chair, similar to one in a dentist’s office, and put on a pair of headphones, which she had plugged into an iPod. Aimee Schultz, a lab engineer, positioned a different kind of mechanical arm—a metal bar, with knobs and a metal probe for a hand—above Mitchell’s chest, in preparation for a series of vibration tests. These were intended to compare the sensitivity of her reinervated skin with her normal skin—her virtual hand with her real one. Currently, Mitchell receives no sensory feedback from her prosthesis. (In New York, when I asked her to squeeze a can of Coke using her artificial hand, with her eyes closed, she was unable to tell me whether, or at what point, she had succeeded.) But Kuiken’s team is working to develop small touch pads that will be added to her fingers and palm for the purpose of sending signals pertaining to temperature, force, and texture back to the corresponding locations on her chest map. The pads must be carefully calibrated. Early testing has suggested, for instance, that Mitchell’s bionic side is slightly more tolerant of extremely cold temperatures; the pads could be adjusted to take that into account.

The vibration tests were set up like an educational video game. Every few seconds, the words “Applying Stimulus” would appear on a screen in front of Mitchell, and the probe, fixed on the Sharpie dot, either would or would not vibrate, at varying amplitudes and frequencies. Her assignment was to indicate whether or not she felt any vibration by using a mouse. It was a painstaking and tedious assignment, and to keep her motivated, a counter on the bottom tallied her “score.”

After high school, Mitchell worked in a meat—processing plant for a few months, cutting giant slabs of beef that were then shipped to various restaurant franchises: Outback, Steak and Ale. “I said to myself, ‘There has got to be something better than this,’ ” she recalled. She decided to join the Marines. Now twenty—six, she is still active in Marine causes—she leads a Young Marines unit for preteens near her home, in Maryland, and volunteers with the Marines Helping Marines program—but she is also a full—time student, having just finished her first year at Howard Community College, where she’s majoring in communications. She visits Kuiken’s lab in Chicago during school vacations, as she did in April; there, her “occupational therapy” training sessions seem to have been culled from a home—economics textbook written in 1953. She cooks, irons shirts, and tosses salads—with and without the prosthesis—for practice. (Lab staffs, who get to join in the tasting component of her evaluation, remember her fried okra and spice cake with special fondness.) During one baking session last year, Mitchell was using her prosthesis to steady a bowl while holding an electric mixer in her right hand. When she turned on the mixer, the current somehow caused her prosthesis to extend without warning, and it shook the bowl, spilling the contents. “I started making one of the doctors nervous,” she said recently. “I was, like, ‘You want to see my new trick?’”

The potential for more useful robot—tricks long ago occurred to Mitchell, and when she returned from lunch on the day of the vibration tests she reminded Blair Lock, another lab engineer, that she wanted her next arm to be equipped with an embedded iPod, as well as a Palm Pilot. “Be careful, we might give you a G.P.S. tracker, too,” Lock said. “We’ll know your every move.” Lock was more concerned, in the interim, with teaching the arm’s computer processor to recognize more subtle motor commands than the three types of locomotion Mitchell currently enjoyed, and he had plugged a laptop into a giant flat—screen monitor with the afternoon’s agenda—advanced signal processing—in mind. “Is that new?” Mitchell asked, eyeing the monitor. “I love DARPA!”

Lock axis another plastic casing to Mitchell’s shoulder and chest, this time with thirteen electrodes and a bundle of wires on the underside. The wires were connected to the laptop, and, once the electrodes had been properly aligned with Mitchell’s chest muscles, a rainbow—colored electromyogram, or EMG, depicting the electrical activity in the muscles, appeared on the monitor. Lock then played the part of physical therapist or personal trainer. “Now elbow up all the way,” he said. “Down all the way. Relax.” Mitchell sat motionless, on the edge of a table, but on the monitor a video image of a man performed the respective actions almost immediately, while the
the arm capable of lifting a hundred and fifty pounds, so that she could impress her guy friends at the gym. She was sweating—the casing is heavy, and takes a toll on one's posture. A staffer at the institute who ordinarily deals with wheelchair upholstery had been working on sewing the electrodes into a custom-fitted Spandex shirt for future use.

Mitchell nodded. She'd remained perfectly still, but the figure on the screen had been busily engaged in what appeared to be a non-stop slow-motion dance workout. Mitchell's chest muscles were becoming sore from overwork.

The exercises continued—there were about a dozen discrete arm motions in this new repertoire—with only one minor hitch, in the case of humeral rotation, when Mitchell's phantom-limb sensation, which has persisted in spite of the reconstruction surgery, seemed to interfere. “You know how my favorite place in the world for my arm is like this, because that's pretty much how it feels?” she said, making an L shape with her right arm against her stomach. “So rotation out is no big deal”—she swung her hand away from her body—but rotation in is weird, because it’s not that big of a movement. For the virtual man on the screen, who lacked legs or a waist, this was not a problem.

“Blair, am I really going to have an arm that'll do all this?” Mitchell asked, sounding excited, after they had finished. “I want my arm to have muscles. Make it a little bit poofy here.” She made a flexed-biceps motion with her right arm. “That'll give you a little more room to put wires in, anyway.” She said she hoped that they'd make the arm capable of lifting a hundred and

Colonel Ling, the supervisor of the DARPA project, is interested in surgical techniques that involve implanting electrodes or computer chips underneath the skin, whether at the periphery (the nerve endings in the stump) or, better yet, in the motor cortex itself. “We need a closed loop that really involves the brain,” he said, explaining that proprioception, or awareness of the body’s movement through space, is a crucial component of fully human arm function, and that only direct sensory feedback to the brain is capable of restoring it. Typing and playing the piano without looking at the keys, for instance, require proprioception.

Scientists funded by DARPA have been experimenting on monkeys for years, using chips to power robotic arms. “We've got signals from monkeys right now that can drive a keyboard,” Ling told me recently. “We have video of monkeys, actually controlling arms, working in 3-D space.” He added, “I know we can do it. At what point do we put them into the human, you might ask? There are always human-use issues, and so on and so forth. If there were no such thing as human-use issues, we would be into humans dramatically sooner. But we have to follow ethics. We have to do the right thing.” He was confident the right thing could be done quickly. “My hope is that we're going to be putting it into humans within the next eighteen to twenty months. Maybe I'm being bold, but, hey, opportunity favors the bold.”

There are, in fact, humans suffering from severe paralysis who have already benefitted from motor-cortex surgery; one research group working toward this goal refers to its implantable sensor as a “neuro-motor prosthesis.” But where otherwise healthy amputees are concerned, Kuiken, for his part, favors the clinically practical—or what he calls the “flying-kid test,” which he thought of one day while playing with his two-year-old son. “He comes in and stumps on me,” he explained. “I get bruises in places I never imagined. But at least they heal.” He is reluctant to recommend for a young and active patient any procedure that could be complicated or undone—chips dislodged, say—in the course of ordinary roughhousing.

“I told Doc he can do whatever he wants to my arm, but he ain't messing with my head,” Mitchell said recently, reinforcing Kuiken's instinct. Since last fall, she has run in two marathons, and in April she mentioned that most of her time outside school was spent attending to the needs of her boyfriend, who was shot in Iraq last November, in an unprotected area between the bottom of his flak jacket and his pelvic brace. Historically, the demands and rigors of war may have provided the impetus for scientific and medical progress, but domestic life is often where the significant advancements are felt first. In Mitchell's case, she said that occasionally she now finds herself reclining on the sofa at home, watching television, and will suddenly realize that the arm propping her head up is her left arm.