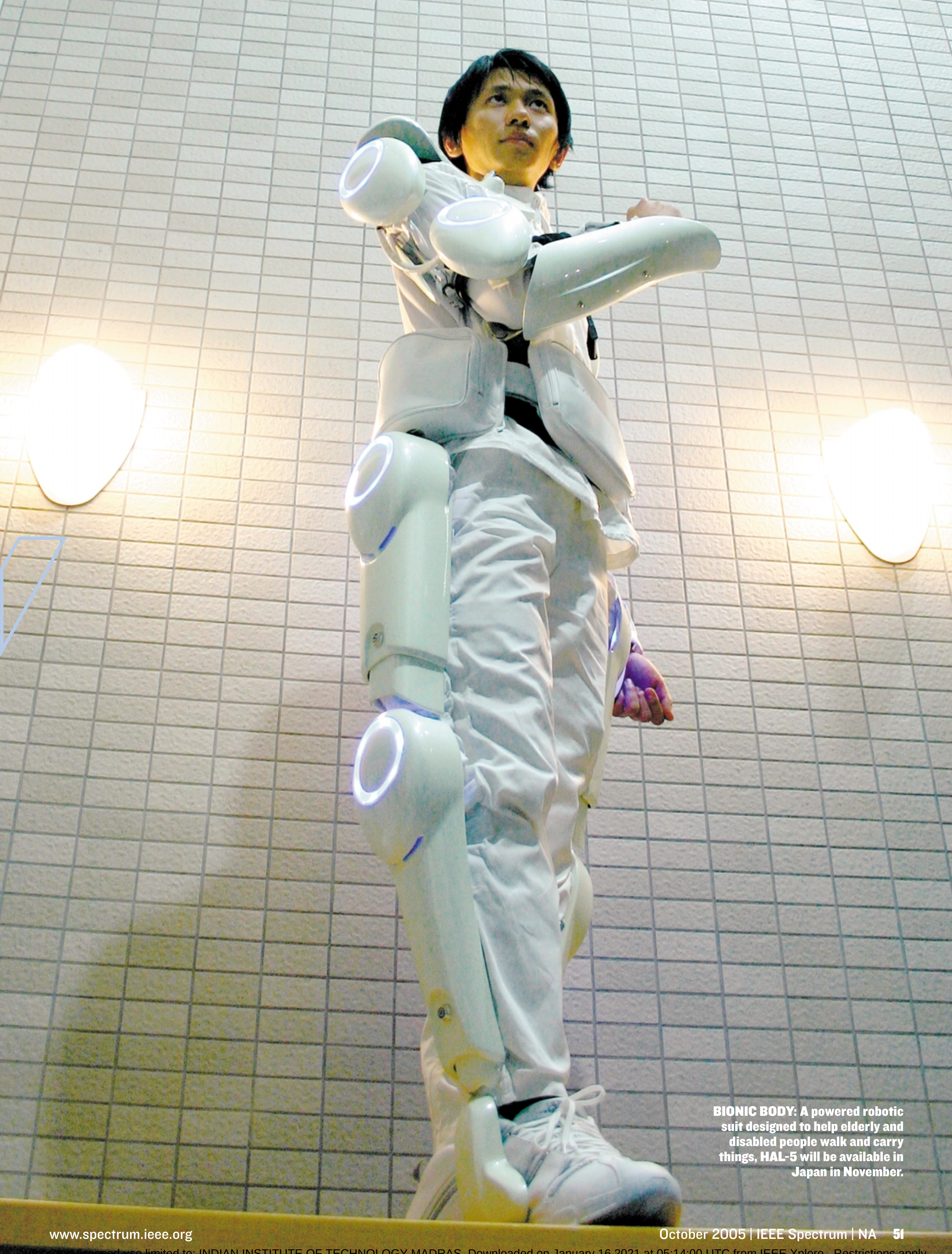
the RISE of the BODY BOTS

EXOSKELETONS ARE STRUTTING OUT OF THE LAB—AND THEY ARE CARRYING THEIR CREATORS WITH THEM

BY ERICO GUIZZO & HARRY GOLDSTEIN



BIONIC BODY: A powered robotic suit designed to help elderly and disabled people walk and carry things, HAL-5 will be available in Japan in November.

SCIENCE-FICTION FANS have long become accustomed to the idea of steely commandos clad in robotic exoskeletons taking on huge, vicious, extraterrestrial beasts, shadowy evil cyborgs, or even each other. Supersoldiers encased in sleek, self-powered armor figure memorably in such works as Robert A. Heinlein's 1959 novel *Starship Troopers*, Joe W. Haldeman's 1975 *The Forever War*, and many other books and movies. In 1999's *A Good Old-Fashioned Future*, for example, Bruce Sterling writes of a soldier dying after crashing in his "power-armor, a leaping, brick-busting, lightning-spewing exoskeleton."

Today, in Japan and the United States, engineers are finally putting some practical exoskeletons through their paces outside of laboratories. But don't look for these remarkable new systems to bust bricks or spew lightning. The very first commercially available exoskeleton, scheduled to hit the market in Japan next month, is designed to help elderly and disabled people walk, climb stairs, and carry things around. Built by Cyberdyne Inc., in Tsukuba, Japan, this exoskeleton, called HAL-5, will cost about 1.5 million yen (around US $13 800).

Meanwhile, in the United States, the most advanced exoskeleton projects are at the University of California, Berkeley, and at Sarcos Research Corp., in Salt Lake City. Both are funded under a $50 million, five-year program begun by the Defense Advanced Research Projects Agency, or DARPA, in 2001. During the past several months, each group has been working on a second-generation exoskeleton that is a huge improvement over its predecessor. Little information about the new models had been officially released by press time, but *IEEE Spectrum* has learned that the Berkeley unit was successfully tested in a park near the campus this past summer and the latest Sarcos model was demonstrated to a panel of military observers at Fort Belvoir, Va., last April.

HAL-5, in Japan, and the systems by Berkeley and Sarcos, in the United States, appear to be the first of a platoon of considerably more capable exoskeletons aimed at real-world uses that may soon, quite literally, be walking near you [see tables of exoskeleton projects]. Most of these systems are designed to help physically weak or injured people gain more mobility or perform rehabilitation exercises. But researchers are quick to mention other commercial possibilities for their creations: rescue and emergency personnel could use them to reach over debris-strewn or rugged terrain that no wheeled vehicle could negotiate; firefighters could carry heavy gear into burning buildings and injured people out of them; and furniture movers, construction workers, and warehouse attendants could lift and carry heavier objects safely.

At long last, exoskeletons, the stuff of science fiction, are on the verge of proving themselves in military and civilian applications. Strap-on robotic controls for the arms and hands—used to remotely operate manipulators that handle nuclear material, for example—have been around for quite a while. But the new anthropomorphic, untethered, and self-powered exoskeletons now strutting out of labs aren't just a bunch of wearable joysticks. They marry humans' decision-making capabilities with machines' dexterity and brute force. They've got the brains to control the brawn.

BIOLOGICALLY SPEAKING, AN EXOSKELETON is the hard outer structure of an insect or crustacean that provides support or protection. But in military research labs, popular fiction, and movies, the term has come to mean a "supersuit," a system that can greatly augment a person's physical abilities.

Now, if exoskeletons are so attractive, why aren't ports, construction sites, and warehouses—not to mention war zones and nursing homes—teeming with them? The reason is that the basic technologies haven't been available. Indeed, all attempts to build exoskeletons in the United States failed until recently. At General Electric's facilities in Schenectady, N.Y., in the 1960s, engineers built a two-armed, bipedal exoskeletal machine dubbed Hardiman, but they could only get one arm to work. At Los Alamos National Laboratory, in New Mexico, in the mid-1980s, scientists envisaged the Pitman suit, a full-body exoskeleton for the infantryman, but it stayed on the drawing board. And at the U.S. Army Research Laboratory at the Aberdeen Proving Ground, in Maryland, in the early 1990s, researchers planned to build a suit that bore some resemblance to the comic-book hero Iron Man; the project never went forward.

PROJECTS IN THE UNITED STATES

HOMAYOON KAZEROONI University of California, Berkeley	Berkeley's new exoskeleton, Bleex 2, is an agile system that lets a person walk and run while carrying heavy loads strapped to a backpacklike frame.
STEPHEN C. JACOBSEN Sarcos Research Corp., Salt Lake City	Sarcos's exoskeleton is a full-body system with powered robotic arms and legs. One of the strongest ever built, it can help a person haul 84 kilograms without feeling the load.
JACOB ROSEN University of Washington, Seattle	A full-arm exoskeleton controlled by neuromuscular signals, it has 7 degrees of freedom. The goal is to help people suffering from various neurological disabilities.
FRANÇOIS G. PIN and **JOHN JANSEN** Oak Ridge National Laboratory, Oak Ridge, Tenn.	A tethered bomb-loading exoskeleton enables a human operator to raise a 1000-kg bomb as if it weighed only 3 kg and load it onto an aircraft.
BENJAMIN T. KRUPP Yobotics Inc., Cincinnati	Based on research at the MIT Leg Laboratory, the RoboWalker orthotic leg brace augments or replaces muscle functions. It is awaiting commercialization.
JOHN DICK Applied Motion Inc., Claremont, Calif.	SpringWalker is a lower-body exoskeleton that can run at 24 kilometers per hour or carry a 90-kg load at a fast walk. It is awaiting commercialization.

These efforts ran into fundamental technological limitations. Computers weren't fast enough to process the control functions necessary to make the suits respond smoothly and effectively to the wearer's movements. Energy supplies weren't compact and light enough to be easily portable. And actuators, which are the electromechanical muscles of an exoskeleton, were too sluggish, heavy, and bulky. "Exoskeletons were always thought of as—you just can't do it," says John A. Main, manager of DARPA's Exoskeletons for Human Performance Augmentation program and a mechanical engineering professor at the University of Kentucky, in Lexington.

But now, he adds, "DARPA is taking the technological excuse off the table." The goal of the DARPA program was to show that it was possible to build a specific kind of exoskeleton: a wearable robotic system to help soldiers carry heavier loads—possibly double the 50 kilograms an unaided soldier is expected to be able to carry—and march faster and longer. It was important to DARPA that the strength not come at the expense of

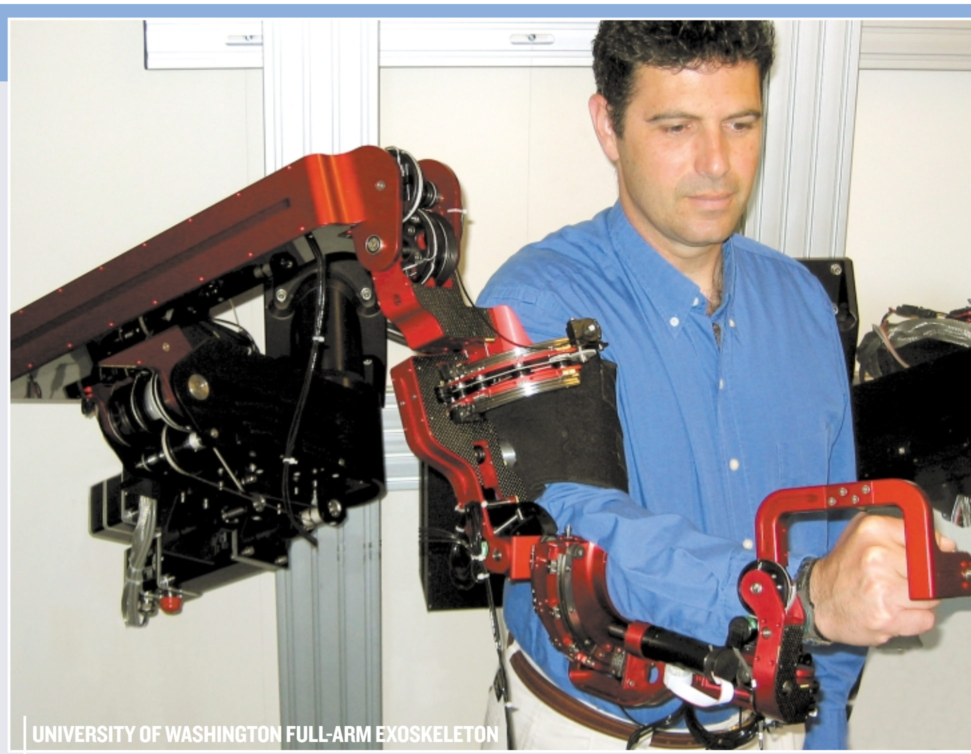
PREVIOUS PAGE: YOSHIYUKI SANKAI, UNIVERSITY OF TSUKUBA/CYBERDYNE INC.

agility: while wearing an exoskeleton, soldiers would still have to be able to crawl under barbed wire, hide in trenches, and go over steep obstacles. But with the suits, they could also carry more weapons, armor, and supplies, as well as go places not accessible to trucks or even tanks.

Main says the new systems by Berkeley and Sarcos showed that it was possible to meet DARPA's requirements. The two teams, he adds, will now have the chance to collaborate with Army research groups to transform their prototypes into real military tools, which could be in field trials within five years.

That's not to say the civilian applications aren't already tantalizing U.S. and Japanese researchers. There are no reliable projections of the commercial potential for exoskeletons, but a 2004 study by the International Federation of Robotics and the U.N. Economic Commission for Europe estimated that accumulated sales of service robots from 2004 to 2007 could reach nearly $10 billion. Service robots, unlike industrial robots used in factories, are designed to interact with people and help them accomplish certain tasks. They include vacuum-cleaning bots, entertainment humanoids, bomb-disarming rovers, and other systems, which soon may well include exoskeletons.

SARCOS POWERED ROBOTIC LEGS



UNIVERSITY OF WASHINGTON FULL-ARM EXOSKELETON

LEFT: SARCOS/DARPA; RIGHT: JACOB ROSEN/UNIVERSITY OF WASHINGTON

Japan, with almost half the world's nearly 1 million industrial robots, is likely to be the place where adoption of exoskeletons will first take hold. The country's rapidly aging population—one in four Japanese will be 65 or older by 2015—and its ambivalence toward admitting foreign laborers have created a shortage of caregivers, and some believe robotic-aided nursing care could be the solution.

Over the last couple of years, Japanese companies have demonstrated a number of exoskeleton-type systems for a variety of applications, some serious, some almost whimsical. For instance, Toyota Motor Corp.'s 200-kg i-foot, which looks like a futuristic chair supported by a pair of legs, walks and climbs stairs, but the wearer has to weigh less than 60 kg. The 3.5-meter-high, two-armed bulldozerlike Enryu, from the small robotics company Tmsuk Co., was built to rescue people from burning or collapsed buildings. More fanciful than functional, the 3.4-meter-high, 1000-kg Land Walker, from Sakakibara Kikai Co., shuffles about at 0.4 meter per second and shoots rubber balls from guns mounted on either side.

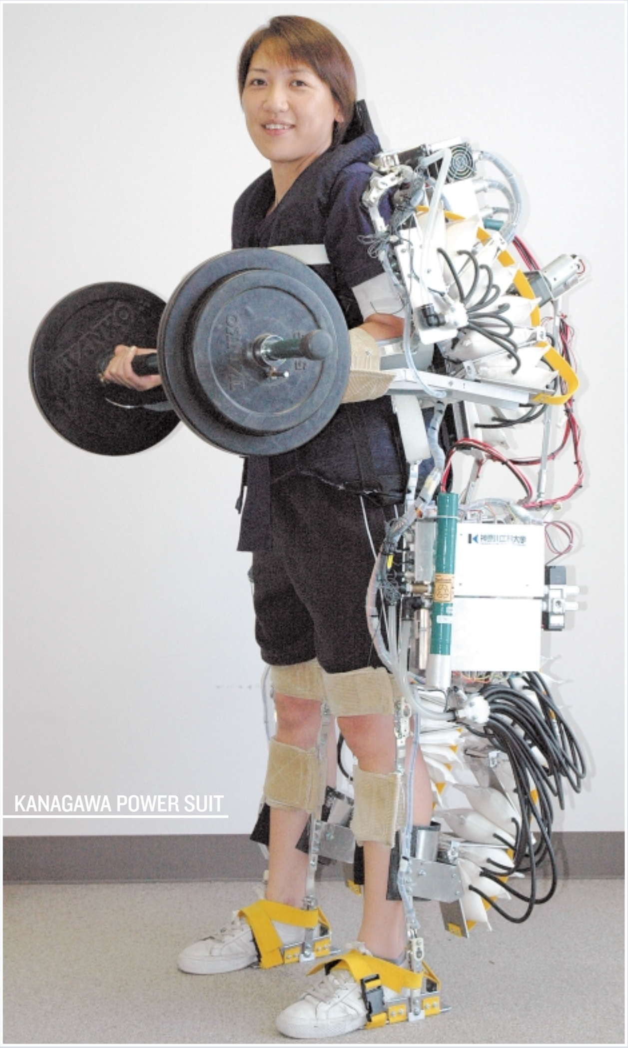
But those machines aren't true exoskeletons. They carry passengers inside enclosed structures and don't map directly onto a person's anatomy. In other words, they aren't the kind of thing you would expect to see in a nursing home helping the elderly get around.

The development of a truly wearable anthropomorphic exoskeleton was the goal of Yoshiyuki Sankai when 10 years ago he started working on HAL, the Japanese system that will be available in November. Sankai, a professor at the University of Tsukuba, 60 km northeast of Tokyo, says HAL (short for Hybrid Assistive Limb) is a full-body suit designed to aid people who have degenerated muscles or those paralyzed by brain or spinal injuries. HAL-5, the system's fifth generation, made its debut this past June at the 2005 World Expo, held in Aichi, in western Japan.

HAL-5's structure consists of a frame made of nickel molybdenum and extra-super-duralumin, an aluminum alloy used in the wings of Japan's famous World War II Zero fighter planes. Further strengthened by plastic casing, the metal frame is strapped to the body and supports the wearer externally, its several electric motors acting as the suit's muscles to provide powered assistance to the wearer's limbs [see photo, "Bionic Body"].

This newest model improves on earlier versions of the exoskeleton in several ways. Previous prototypes helped ailing humans to stand up, walk, climb stairs, and perform a range of other leg movements—one user was able to leg-press 180 kg (almost 400 pounds)! HAL-5 goes a step further by incorporating an additional upper-body system that helps users lift up to 40 kg more than they normally could. Wearing the suit, a healthy adult male can lift 80 kg, roughly double his typical 30- to 40-kg capability.

"But a human would quickly become tired holding a heavy load," Sankai points out. "This machine can continue holding a



KANAGAWA POWER SUIT

PROJECTS IN ASIA

YOSHIYUKI SANKAI University of Tsukuba, Japan	HAL-5 is a full-body suit with electric actuators designed to help elderly and disabled people walk. It will be available in Japan in November for about US $13 800.
KEIJIRO YAMAMOTO Kanagawa Institute of Technology, Atsugi, Japan	A full-body exoskeleton with pneumatic actuators powered by batteries, the Power Suit allows a nurse to carry an 85-kilogram patient without breaking into a sweat.
KAZUO KIGUCHI Saga University, Saga City, Japan	An upper-limb exoskeleton that translates neuromuscular signals from arm muscles into robotic motion. Designed to assist physically weak or injured people.
HIROSHI KOBAYASHI Science University of Tokyo	Lightweight upper-limb "muscle suit" that uses soft, flexible pneumatic actuators. Designed to help paralyzed people with their daily activities.
MUNSANG KIM Korea Institute of Science and Technology, Seoul	An exoskeleton master arm with pneumatic actuators for controlling a humanoid robot's arms. The user feels the same force as the robot does.

heavy weight for 5 or 10 minutes, no problem," he adds, speaking from his office at Cyberdyne, which he set up as a venture company on the Tsukuba campus to commercialize the suit.

Another major improvement is the elimination of the bulky backpack used in HAL-3, which contained the Linux-based control computer and a Wi-Fi communications system. Those components were shrunk to fit into a small pouch that is now attached to the belt. The suit is powered by both nickel-metal hydride and lithium battery packs. Currently, a full charge lasts for 2 hours and 40 minutes, with both the upper- and lower-body parts in action. HAL-5 weighs about 21 kg, but Sankai says wearers don't notice the suit's weight, because it supports itself.

The exoskeleton has also undergone a major face-lift. It now incorporates smaller dc motor actuators, which are positioned at the shoulders, elbows, hips, and knees. This improvement, along with the addition of the plastic casing that covers and strengthens the frame, means the new suit has shed the knobby, bare-bones look that characterized HAL-3 in favor of a sleek appearance resembling outfits seen on "Star Trek."

Sankai and his team developed two control systems that work together to command HAL-5's limbs. The first one, the bio-cybernic system (a term coined by Sankai), monitors electric currents known as electromyogram, or EMG, signals on the wearer's body. These signals flow along muscle fibers when a person intends to move. Coin-size sensors attached to the wearer's skin near the shoulders, hips, knees, and elbows pick up the signals and feed them to the control computer, which then triggers the actuators to put the robotic arms and legs into action.

The job of the second control system is to let the wearer and suit move together more smoothly. It stores walking patterns—generated the first time the person tries out the suit—that are used to keep the suit's limbs always in sync with those of the wearer. This system can be fine-tuned so the exoskeleton matches each wearer's distinct gait, which is especially important if, say, the person has one leg less capable than the other. It also allows certain disabled people, whose EMG signals aren't detectable, to use the suit. "If the user has trouble in the spinal cord or in the brain, we can't use the bioelectric signals," Sankai says. "In this case, the robotic autonomous control system activates itself automatically once the user starts moving."

Sankai now spends time every Saturday in his lab at Tsukuba fitting patients with the first commercial versions of the suit. He says it takes two months to calibrate the control systems so that they work optimally for each individual. He is also receiving requests from hospitals and rehabilitation centers. "By the end of November, I expect we can provide 10 or 12 sets," he says. Though the suits can be bought outright, he would rather lease them "because the technology is always improving, and then we can exchange them for newer versions." The yearly leasing price, he says, will be set between 300 000 and 400 000 yen (about $2750 and $3670).

MEANWHILE, ON THE OTHER SIDE of the Pacific Ocean, a research group from the University of California, Berkeley, is hard at work testing the capabilities of its own advanced exoskeleton. In fact, a few months ago, team members chose the heavily wooded trails of Tilden Park, just north of the Berkeley campus, to try out their latest creation. They were there a few times this past summer to field-test a new generation of the Berkeley Lower Extremity Exoskeleton—Bleex for short.

The group has been working on the machine, Bleex 2, and its predecessor, Bleex 1, for the past five years. Bleex 1 was unveiled early in 2004, and so far the Berkeley team hasn't officially released

KANAGAWA INSTITUTE OF TECHNOLOGY

The new HAL-5 suit has shed the knobby, bare-bones look that characterized its predecessor, in favor of a sleek appearance resembling outfits seen on "Star Trek"

much information about the sleeker, stronger Bleex 2. But some details made available to *Spectrum* confirm that the new system is a significant improvement over the older unit. Bleex 2, like its predecessor, has two electromechanical legs that strap to the outside of the wearer's legs. At waist level, the robotic legs connect to a backpacklike frame. Mount any type of heavy load on that frame and Bleex will carry the bulk of the weight for you. There are no joysticks or other manual controls. You can walk, run, squat, twist, kneel—even dance, if you like—and the exoskeleton will command its powered legs to follow your moves.

But while Bleex 1 was relatively large and bulky—each of its robotic legs a tangle of hydraulic actuators and electronic modules encased in plastic covers—Bleex 2 is compact and light, weighing one-third as much, only 14 kg. The new design reveals that the Berkeley team has successfully miniaturized most of the machine's components. Basically, the new legs consist of elongated metal tubes, not much thicker than hockey sticks, that now encapsulate most actuators and electronic circuitry. Photos of Bleex 2 made available to *Spectrum* (but not approved for publication at press time) reveal no exposed cables, circuits, or protective plastic covers.

There are also improvements to the way the exoskeleton powers its robotic legs, although details were not forthcoming. Bleex 1 relied on hydraulic actuators, which received high-pressure fluid from a pump coupled to a small gasoline engine. The actuators are essentially cylinders with sliding shafts that move to produce the desired torque at each of the joints in the mechanical legs. With this system, the wearer could walk with Bleex 1 at nearly 2 meters per second while hauling 34 kg. Bleex 2, it seems, also relies on hydraulic actuators. But researchers declined to say whether the power source is still an internal-combustion engine or something else, such as a battery-powered system.

Nevertheless, *Spectrum* has learned that a person wearing Bleex 2 can run at speeds exceeding 2 meters per second while carrying a payload of 45 kg. That revelation alone is an indication that the Berkeley team has built a very agile exoskeleton. It's a machine that has been on some rough rides at Tilden Park, according to a member of the Berkeley team. So far, they've used it to sprint along uneven gravel paths and march up and down steep hills, with the wearer carrying a load strapped to the backpack part of the frame.

For its part, the Salt Lake City–based Sarcos team, led by roboticist and inventor Stephen C. Jacobsen, has been working on what may be one of the strongest exoskeletons ever built. Earlier this year, at the demonstration the group did in Fort Belvoir, an engineer wearing the Sarcos robotic system was able to carry 84 kg—about the weight of an average size washing machine—without feeling the payload at all. Jacobsen, Sarcos's CEO and a mechanical engineering professor at the University of Utah, says that the new exoskeleton supports the payload's entire weight even if the wearer stands on one leg.

Like Bleex 2, the latest Sarcos system is a second-generation model that improves substantially over its predecessor. Jacobsen says that while wearing the exoskeleton, you can walk

NEOGENTRONYX

MECHA: IT'S MEGA

IT'S BIG. IT'S BAD. And, unfortunately, at the moment, it barely moves. The colossal, 5.5-meter-high, 1360-kilogram Mecha exoskeleton sits in Carlos Owens's backyard in Wasilla, Alaska, its legs locked into position to prevent the hydraulic fluid that helps move the monster's limbs from losing all pressure.

Powered by an 18-horsepower (13.4-kilowatt) Briggs & Stratton engine, Mecha cost Owens US $25 000 and took about a year and a half to build. This past May, Owens climbed into the pilot seat and took Mecha for its first walk: half a dozen steps, each measuring about 20 centimeters.

According to Owens, Mecha's limbs mimic the pilot's movements using joystick controls that track arm and leg position. Such a system gives the pilot the "illusion of being in a suit of armor rather than on a bipedal vehicle," he says.

An ironworker who spent time in the U.S. Army Reserve, Owens is convinced that what he calls an "enclosure exoskeleton" is a safer, more practical choice for the battlefield than either of the exoskeletons being developed for DARPA. He scoffs at the tens of millions DARPA has spent so far and believes that for that amount of money the military should at least get something that will not only help transport a soldier in a war zone but also protect him.

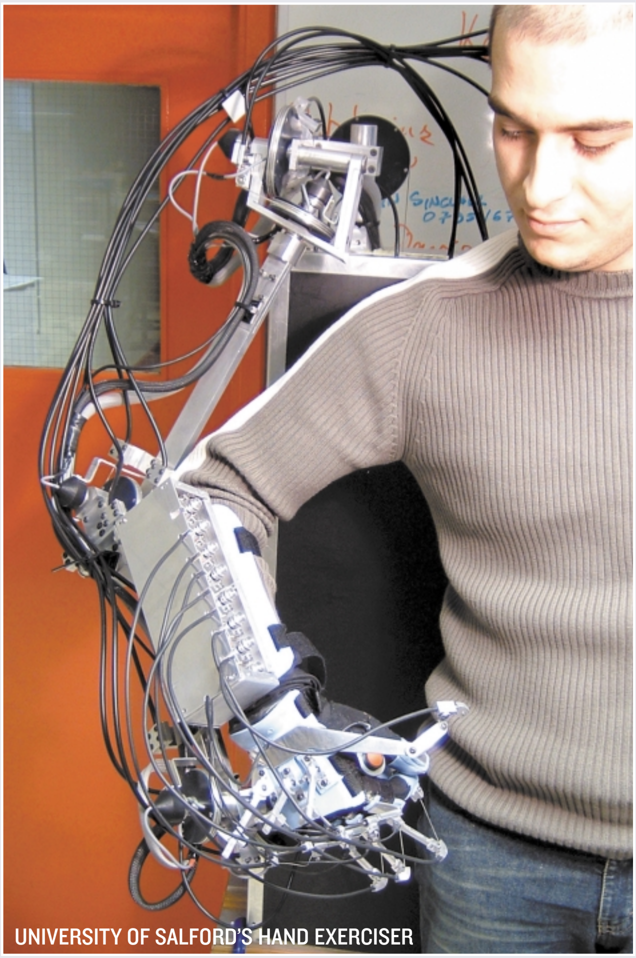
Owens showcases his prototype Mecha at http://www.neogentronyx.com and on eBay ($40 000 plus $6000 shipping, with no takers at press time), but he hasn't showed it off in a public test-drive. Walking in this first version of Mecha is very awkward, he admits, and it's too big to be easily transported to a place where he could demonstrate it.

Mecha is certainly in no shape to take on the do-it-yourself exoskeletons in the annual weight-lifting competition sponsored by *Servo Magazine*, called the Tetsujin [Japanese for "iron person"] Challenge. But with time and money, Owens believes, he could improve Mecha as a prototype for machines that eventually will help people fight wars, put out forest fires, and construct buildings.

—H.G.

and run, and if you stumble, the system is fast enough to readjust its powered limbs to keep the payload's weight off your body.

The exoskeleton relies on a network of force sensors that are in touch with the wearer's body at certain points, such as underneath the feet. These special sensors, developed by Sarcos, feed data to a control computer that in turn commands the robotic limbs to move in harmony with the wearer's arms and legs without ever obstructing them. Jacobsen calls this method "get out of the way" control, and he says using the robotic suit requires no training. "You can step into the exoskeleton, and you can immediately run it," he says.


UNIVERSITY OF SALFORD'S HAND EXERCISER

PROJECTS IN EUROPE

DARWIN CALDWELL and NIKOLAOS TSAGARAKIS University of Salford, Manchester, England	An exoskeleton hand exerciser rehabilitates hand muscles by allowing the wearer to accurately repeat finger motions. It is used in conjunction with virtual reality exercises.
ANTONIO FRISOLI Scuola Superiore, Sant'Anna, Pisa, Italy	An arm and hand exoskeleton, L-EXOS (Light Exoskeleton) can be used for human interaction with virtual environments and teleoperation tasks.
GÜNTER HOMMEL Technische Universität, Berlin	A lower-extremity orthotic exoskeleton driven by electric actuators is designed to assist people in rehabilitation exercises and also in everyday movements.

According to Jacobsen, what makes an exoskeleton an extremely hard problem is that conventional, off-the-shelf components won't work. Sarcos had to design and fabricate each piece and, in parallel, integrate all of them into its system. The exoskeleton's power unit was one of these many pieces the company had to engineer painstakingly. It's a special internal-combustion engine that can use a variety of fuels and deliver enough hydraulic power to the actuators to meet the great strength and speed the robotic limbs require.

But even more challenging, Jacobsen says, was developing yet another component: the servo valves that control the flow of the hydraulic fluid into the actuators. The valves had to be small, extremely reliable, resistant to high pressures, and highly efficient to preserve precious power, not to mention that some of their parts had to be machined to micrometer tolerances. To make things even harder, so many complex physical processes occur in the valves, Jacobsen insists that simulation software couldn't help in the design. His group, therefore, had to go through several iterations of prototypes to get the valve it needed.

Sarcos is now preparing for demonstrations scheduled over the next few months. Team members are especially busy with the exoskeleton's upper-extremity system, which will add strength to the wearer's arms. A person wearing the full-body system will be able not only to carry a payload on a backpack but also lift heavy items, a capability that is particularly useful for logistics operations such as loading and unloading cargo vehicles and moving things in a warehouse.

THESE ADVANCES MAKE IT POSSIBLE to envision a future in which exoskeletons are part of our daily lives. Perhaps someday they'll help you heft an 80-kg washing machine around the laundry room all by yourself. Or maybe you'll be entertained by the spectacle of competitors using them in new, tech-based extreme sports. How about a transcontinental marathon that really tests the racers' "metal"?

It might sound preposterous, but enthusiastic amateur exoskeleton makers are already competing in an annual exoskeleton-enabled weight-lifting competition called the Tetsujin Challenge, sponsored by the do-it-yourself robotics monthly *Servo Magazine*. And in a class by itself is the 5.5-meter-high contraption designed by Carlos Owens [see sidebar, "Mecha: It's Mega"].

You're not likely to see exoskeletons battling extraterrestrial monsters anytime soon. But before long, it might not even occur to you to gawk at the sight of a person strapped to an exoskeleton bringing home the groceries or going for a stroll in the park. ■

With additional reporting by Jean Kumagai in New York City and John Boyd in Yokohama, Japan.

TO PROBE FURTHER

For a photo gallery of many other exoskeletons and wearable robotic systems, visit http://www.spectrum.ieee.org.

For exoskeleton-related discussions and demonstrations, see the IEEE International Workshop on Robot and Human Interactive Communication, to be held in Hatfield, England, from 6 to 8 September 2006 (http://www.ro-man.org/) and the IEEE/RSJ International Conference on Intelligent Robots and Systems, to be held in Beijing from 9 to 14 October 2006 (http://www.iros2006.org).

For more on Japanese exoskeleton projects, see the August 2005 issue of *Advanced Robotics* (http://www.rsj.or.jp/AR/) and the October 2004 issue of *Journal of Robotics and Mechatronics* (http://www.fujipress.jp/JRM).

CENTRE FOR ROBOTICS AND AUTOMATION, UNIVERSITY OF SALFORD