The Weekly Newsmagazine of Science

SCIENCE NEWS

June 30, 2001
SEMI-ANNUAL INDEX
Vol. 159, No. 26
Pages 401-416

Out in a Limb

Dances with Robots

The military is betting millions that technology can turn soldiers into superhumans

By PETER WEISS

The legs of an aluminum skeleton hang from Homayoon Kazerooni's backpack, its feet bolted to his boots. The lanky metal framework is part of an experimental robot, powered by a chain saw engine, that rides piggyback on Kazerooni, a mechanical engineering professor at the University of California, Berkeley. He's trying to walk with the contraption, which weighs as much as a grown man. As long as the engine is on, the robot walks with him, and he doesn't even feel the extra weight.

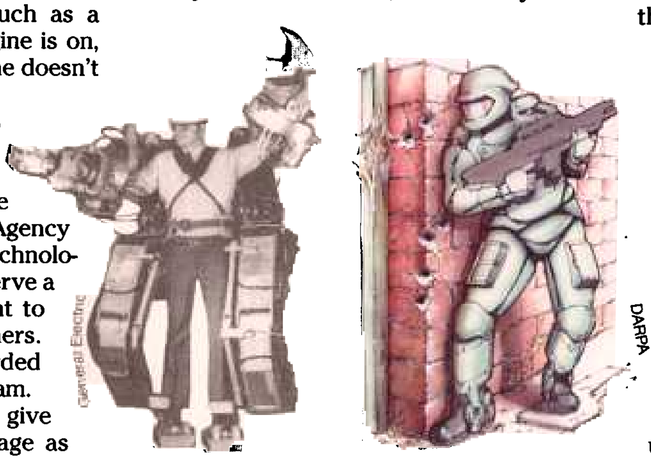
Kazerooni and his colleagues have made what may be the world's most advanced motorized exoskeleton. The Defense Advanced Research Projects Agency (DARPA) regards exoskeleton technology as promising enough to deserve a $50 million, 5-year commitment to fund Kazerooni's lab and others. This spring, the agency awarded first-year grants under the program.

Exoskeletons may one day give U.S. soldiers a crucial advantage as warfare becomes increasingly urban, says Ephrahim Garcia, manager of the new DARPA program. Since troops are less able to use their armored vehicles to fight in confined urban battlefields, military planners want to fasten the armor, heavy weapons, and advanced electronics onto the foot soldiers themselves. Without heavy-duty mechanical support from something like an exoskeleton, however, people would collapse under the load.

Besides their military uses, Garcia notes, exoskeletons could also help civilians, from disabled people and construction workers to rescuers working in fires and natural disasters.

Natural exoskeletons abound, encasing critters ranging from crickets to crabs. In more human contexts, robotic exoskeletons are most familiar from science fiction and comic books. In Robert A. Heinlein's 1959 novel *Starship Troopers* (G.P. Putnam's Sons), swift, merciless warriors in powered suits wreak havoc on their enemies with missiles and hydrogen bombs. To Heinlein, "the beauty of a powered suit [is that] you don't have to think about it. You don't have to drive it, fly it, conn it, operate it: you just wear it and it takes orders directly from your muscles . . . ."

Four years after Heinlein's book came out, Marvel Comics introduced the character Iron Man, a rich industrialist encased in a homemade iron exoskeleton that enables him to lift tons at a time, fire deadly radiation beams, and even fly. In the 1986 film *Aliens,* Sigourney Weaver as Lt. Ripley straps herself into an industrial loader—like a forklift with legs—to battle the hideous, mucus-covered alien queen.



General Electric

DARPA

An early attempt to outfit a person with a robotic strength-amplifying machine produced the crude 1960s Goliath known as Hardiman 1 (left). Engineering advances may soon lead to form-fitting, flexible exoskeletons like the one on the trooper in this artist's rendering (right).

Actual efforts to make motorized exoskeletons date back to the 1960s, although design studies began well before. Hollywood's human-cum-forklift idea may have arisen from a 1965 project at the General Electric (GE) Research and Development Center in Schenectady, N.Y. There, a design for a self-standing exoskeleton powered by hydraulics and electricity came to life as a hulking contraption called Hardiman 1.

The robot, as heavy as a car, would have enabled a person to lift a refrigerator as though it were a bag of potatoes. However, the machine's inventors could only get one arm of the device to work. And attempts to operate both legs at once would lead to "violent and uncontrollable motion," according to an old GE report on the project.

Since then, most development has focused on components for exoskeletons rather than complete systems. For instance, before Kazerooni and his colleagues built their new exoskeleton, they had devised a number of so-called extenders, such as force-amplifying arms.

Even the new exoskeleton is not a full-body device. It's only a "lower extremity enhancer," known by the acronym Lee, the researchers say. The device has attracted DARPA's eye, but the Berkeley group created the machine during the past 6 years with funding from nonmilitary sources.

At the University of Utah in Salt Lake City and the nearby spin-off company Sarcos, a team led by Stephen C. Jacobsen has been creating so-called master-slave telerobotic devices. They include a slave limb that follows the motions of a person's arm that's yoked into a master arm across the room.

Although this type of technology has been around for decades, used for instance, to handle radioactive materials, the latest versions are more responsive and dexterous than past device. A full-body suit that Sarcos developed implements the same idea on a larger scale. Whatever the wearer of the sensor-equipped harness is doing—from calm sitting to wild dancing—a humanoid robot would instantly do the same thing.

Researchers at Oak Ridge (Tenn.) National Laboratory have developed a lifting machine that can amplify hand motions enough to manipulate tremendous loads with the precision of a jeweler—a difficult combination to achieve. The experimental device, developed for loading weapons into aircraft, can sustain jolts without getting jitters that often crop up when a control system is suddenly disturbed, says François Pin, one of the machine's inventors. The lifter enables its operator to raise a 2,200 kilogram bomb as if it weighed only 4 kg.

Looking at these and other developments in exoskeleton-related technology, Garcia believes that "all this combined together makes this a good time" to try again for the complete package. "We're going to take some of these technologies that are almost ready . . . and push them over the edge," he says.

The result may be some formidable

One-person air car may let troops fly

Although it looks like the fantasy of some 1950s futurist, a new type of flying platform may carry 21st-century soldiers into battle. Work on the platform is taking place as part of a recently launched military program that aims to develop motorized robotic frameworks, or exoskeletons, for soldiers.

While those devices may endow troops with remarkable strength (see main story), they'll lack a vital feature of the superman dream—flight.

That missing piece has been the goal of the company Millennium Jet of Sunnyvale, Calif., since the mid-1990s. The company has designed and built a prototype of a one-person flying machine, called Solo Trek XFV, on which a pilot stands.

A prototype one-person flyer recently demonstrated enough thrust to be able to take off carrying a person.

Above the pilot's head, a pair of powerful counter-rotating fans provide propulsion. According to the design specs, the rotors ought to enable the aircraft to take off vertically, fly horizontally at more than 70 miles per hour, and then land vertically again on a clear patch of ground as small as a dining-room table. The innovative craft is expected to fly at altitudes up to 2,400 meters and carry a maximum load of 200 kilograms. None of these parameters has yet been field-tested, however.

By awarding a $1 million first-year grant to Millennium Jet in December 2000, the Defense Advanced Research Projects Agency (DARPA) became the first outside investor to support the company's project. Why is DARPA interested? The machine "allows a person to get three-dimensional in the battle space," explains DARPA exoskeleton program manager Ephrahim Garcia.

"We have a system that gives people capabilities that they don't have right now," adds company head Michael Moshier. Including Millennium Jet's flyer in the larger DARPA-funded exoskeleton program, he says, "was a natural marriage," but the company is promoting Solo Trek as a civilian craft, too. —*P.W.*

prototype machines. Garcia says his current goal is to equip a soldier with an exoskeleton that will make him or her 3 to 10 times stronger than without it. Fighters would smoothly wield 50-kg weapons while simultaneously wearing 20 kg of armor.

Compared with a currently equipped U.S. marine, who is required to march 4 kilometers per hour carrying as much as 50 kilograms of equipment, an exoskeleton-equipped marine would be able to move about three times that fast while carrying more than double the load, Garcia predicts. The leatherneck exoskeleton would probably cost no more than the price of a motorcycle, he adds.

The leap from today's technology to an exoskeleton meeting Garcia's goals is a huge one. Among the three DARPA contractors working on exoskeletons for ground troops—Kazerooni's lab, Jacobson's operation at Sarcos, and Oak Ridge's robotics group—only Kazerooni's team has actually demonstrated a powered exoskeleton.

Millennium Jet in Sunnyvale, Calif., which is also receiving DARPA funds, is well under way with developing a personal flying machine known as Solo Trek XFV (see sidebar). The vehicle is a one-person device but not a wearable exoskeleton.

To build a system in which a robot shadows every move a person makes is a complex undertaking. After detecting the motion and gauging its speed and force, the robot must translate those readings into a parallel motion by some of its components. All the while, other exoskeleton components have to adjust to maintain the system's balance.

Gravity, friction, thermal effects, sensor errors, and other subtle influences play into the human-robot interactions. Managing it all requires sophisticated mathematical models based on fundamental physics and control theory that builders must program into the machinery, says Oak Ridge's Pin. The researchers at all the DARPA-funded labs are creating these models as they go.

Neither such a computer program nor the motions of an exoskeleton itself have to be off by much to cause the wearer discomfort or fatigue, says Jacobsen. Less than 2 kg of misplaced weight on a person's arm, for instance, can wear a person out in just 10 minutes or so, he says.

Bigger errors may be dangerous. Industrial robots sometimes injure or kill people who stray too close. Powerful exoskeletons will be embracing their wearers when something goes wrong, Pin notes.

Countless challenges to exoskeleton designers involve such details as framework materials, actuators, and sensors, plus the heat, noise, and weight of each of these components. Nothing looms larger, however, than the need for a compact, portable, and ample source of power. Not only do the mechanical motions of the exoskeleton and its various control systems draw a lot of power, but soldiers are increasingly outfitted with computerized communications and information gadgetry that also drinks up energy. Garcia has hired several analysts specifically to investigate this issue.

As a group, the DARPA contractors are pursuing several innovative solutions for powering exoskeletons. These include chemical reactors, a coffee-cup-size turbine that whirls a half-million revolutions per minute, miniaturized internal combustion engines, and fuel cells that feed supercapacitors that can release power in bursts. Each offers its own advantages and disadvantages.

Internal combustion engines and some chemical reactors, for instance, run hot and so will require extra insulation to protect the wearer. Says Garcia, "If you can't do the power, everything else is, in some sense, academic."

Using a relatively heavy gasoline engine, as Kazerooni has done with his leggy Lee, is clearly not the way to power an exoskeleton. Equipped with a fuel tank that holds about 1 liter, the engine runs Lee for only about 15 minutes. Then, as the power dies, another flaw of the Berkeley group's first exoskeleton becomes obvious. Unless someone races to scoot a chair under the wearer, the suddenly burdensome load will bring him helplessly to the ground.

Perhaps the worst strike against the prototype is that it "imposes constraints on the person, like a tight shoe or like clothes that aren't comfortable to you," confesses Kazerooni.

Yet making even a crude device that can pull its own weight provides the Berkeley team with an important confirmation. "It verified some of our control theories, which shows we are going in the right direction," Kazerooni says.

Even as the research teams work out the early details of their exoskeleton designs, some of the investigators are looking beyond this round of experimentation. Kazerooni, for one, anticipates that exoskeletons of the future will be "invasive"—not just worn but partially implanted within a person's musculature and nervous system.

Jacobsen says he's thinking in the opposite direction—about putting more human nature into the machines. His idea is to build an exoskeleton intelligent enough to take care of the soldier wearing it. If the human trooper is badly wounded, the machine would say to itself, in effect, "Take this guy home." □