IN PURSUIT OF THE PERFECT POWER SUIT

A longstanding quest to augment human performance with robotic exoskeletons takes a softer approach

By **Warren Cornwall**

A lone soldier stands in a dark alley, eyeing a door. Even though he's covered in bulky armor, he charges forward and bursts through, and is engulfed in a barrage of gunfire. Rather than retreat, the soldier stands tall as bullets ping off him harmlessly.

This isn't a trailer for the latest superhero movie. It's an animation produced by the U.S. military, designed to show off its vision for a brawny robotic exoskeleton that it hopes to deploy with elite commandos. Dubbed the Tactical Assault Light Operator Suit, or TALOS, it's the focus of a multimillion dollar research project catalyzed by a commando's death during a hostage rescue in Afghanistan. The TALOS's name pays homage to a metal giant of Greek mythology who guarded the island of Crete, effortlessly circling it three times a day. More casually, it is called the Iron Man suit.

The TALOS is just one part of a much larger, global research push to develop exoskeletons that would endow people with superhuman strength and endurance. But imagining Iron Man in comic books and movies has proven easier than building him. The effort is littered with failures. A predecessor to the TALOS, called the Human Universal Load Carrier (HULC), was shelved after it proved impractical, exhausting users instead

A soldier tries out a so-called soft exosuit at the Army's Aberdeen Proving Ground in Maryland. Tests have found it can help a person walk more efficiently.

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of supercharging them. And some scientists are skeptical that the TALOS and similar heavy, hard-bodied exoskeleton designs will work anytime soon, saying they often fail to address fundamental physiological issues.

Improving on the effortlessness of the human stride—little more than a forward lean and a flick of the calf—turns out to be a daunting engineering challenge. Building a machine to help someone with a disability is one thing, but "it's very difficult from a design perspective to augment human walking and running, because we're so good at it," says Hugh Herr, an engineer at the Massachusetts Institute of Technology (MIT) in Cambridge. The exoskeletons developed so far, he says, are too bulky and tend to fight the natural rhythms of the body, which turns them into "fancy exercise machines."

As a result, some researchers are lowering their sights. They are taking a softer, smaller approach, building suits that resemble running tights hooked to motorized wires, or a modest ankle brace. In just the last few years, they have finally achieved a long-sought goal: creating an exoskeleton that actually saves the user energy while walking on a level treadmill.

That achievement is a long way from a supersoldier smashing through a door, but it is raising hopes that machinery and microprocessors can truly augment a healthy human. "I think we're in the stage where the Wright brothers can get the plane up for a bit, but it doesn't stay up for long," says Dan Ferris, a leading exoskeleton scientist at the University of Michigan (UM), Ann Arbor.

MILITARY LEADERS seeking to give soldiers more strength, stamina, and protection have long dreamed of something similar to Marvel Comics's Iron Man, whose powers came from a robotic suit. In the late 1960s, the U.S. Office of Naval Research funded development of Hardiman, a massive, 680-kilogram exoskeleton built by General Electric Global Research. Hardiman was ultimately abandoned, but the idea didn't die.

In 2000, the Defense Advanced Research Projects Agency (DARPA), a Pentagon agency best known for helping invent the Internet, radar-evading stealth aircraft, and pilotless drones, began funding research into exoskeletons that could improve combat performance. The results included a variety of high-tech hinged metal leg braces. One design from a lab at the University of California (UC), Berkeley, evolved into the HULC.

By 2011, defense contractor Lockheed Martin, which had licensed the rights to use the UC Berkeley system, was ready to test an updated HULC, which featured slimmed-down braces and motor-driven joints, at the U.S. Army's Natick Soldier Research, Development and Engineering Center in Massachusetts.

The hype was substantial. The HULC "will enable soldiers to do things they cannot do today, while helping to protect them from musculoskeletal injuries," declared Lockheed project manager Jim Ni in a press release. The HULC would enable soldiers to carry 90 kilograms up to 20 kilometers on a single battery charge, the company claimed.

VIDEO

To watch a video, go to http://scim.ag/6256_vid

The celebration was short-lived. When soldiers strapped into the 40-kilogram suit and walked on a treadmill, tests showed they burned more energy than they did walking unaided. In one trial involving eight HULC wearers, their heart rates jumped by 26% on average, while their oxygen consumption rose 39%, compared with when they didn't use the machine.

One big problem was that the HULC forced wearers to walk in an unfamiliar way, says Karen Gregorczyk, a biomechanical engineer at the Army's Natick center who led the tests. That difficulty was compounded by a lack of coordination between human and machine. "It's trying to kick your leg forward and you're not ready to kick your leg forward," says Gregorczyk, who spent a half hour trying the suit. "It was a workout."

Today, the last of the HULC prototypes are parked at a company lab in Orlando, Florida. Work is also on hold on XOS 2, a similar DARPA-born exoskeleton that Raytheon acquired.

THE HULC'S DOWNFALL hasn't stopped the military from trying again to go big. Now, the focus is on the TALOS, a brainchild of former Navy Admiral Bill McRaven, who until last year led the Pentagon's Special Operations Command (SOCOM). After a SEAL commando died, shot while entering a room during a hostage rescue, McRaven says someone asked him why the military still didn't have a good way to protect soldiers in those situations. "He said, 'Where is our Iron Man suit?'" recalls McRaven, now chancellor of the University of Texas system. "I didn't have a good answer for him." In early 2013, McRaven's command launched a 5-year research program.

From the start, the TALOS had a touch of Hollywood, and not just in the promotional video. Among the project's contractors was Legacy Effects, a California company that built the suits for the *Iron Man* movies. "Science fiction can drive the science," McRaven says. "We may never get something that looks just like Iron Man, but that's what we're looking for."

A team of technicians trails a military exosuit tester, gathering data that will reveal whether the device is aiding—or hurting—the soldier's performance.

PHOTOS: PAUL FETTERS (2)

So far, there are few public details about the TALOS's design. In written responses to questions from *Science*, Lieutenant Commander Matt Allen, a SOCOM spokesman, painted a picture of a full-body exoskeleton capable of carrying heavy body armor, as well as antennae and computers to provide battlefield information, and sensors to track the soldier's physical condition. Photos and promotional video of prototypes show devices that bear a strong resemblance to the HULC, with rigid, hinged frames running down the legs.

But Russ Angold, an engineer and cofounder of the Richmond, California, company Ekso Bionics, says the TALOS designers have learned from the shortcomings of past designs. The company was created to commercialize the UC Berkeley exoskeleton, and

Giving soldiers a robotic boost

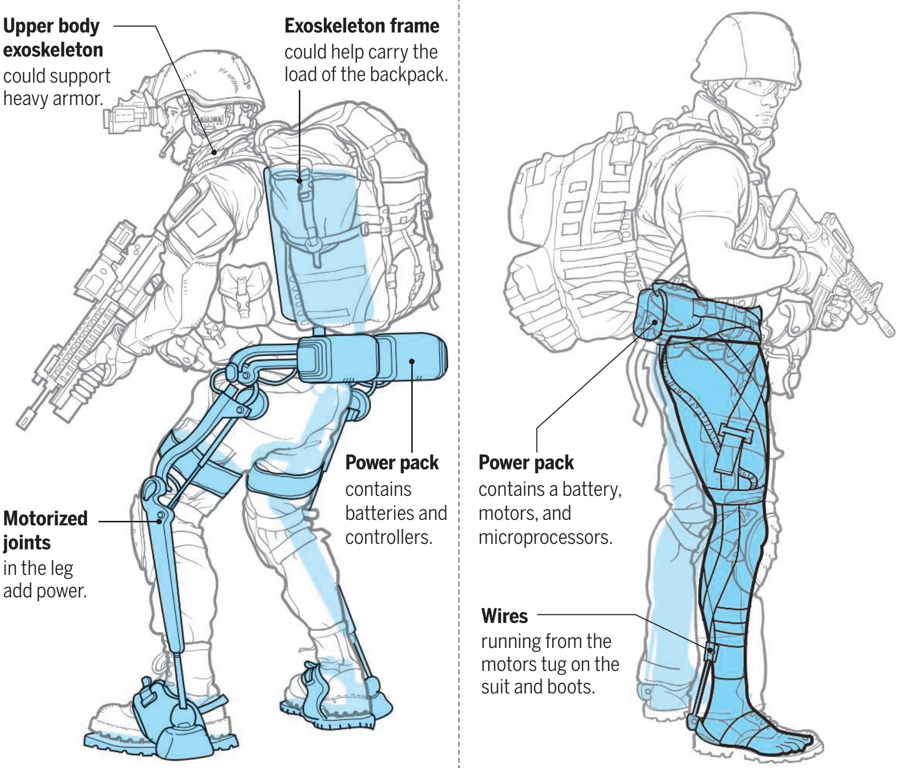
The U.S. military, and others around the world, are trying to build exoskeletons to enhance soldiers' strength and stamina. Several designs are in development.

Rigid exoskeleton

A rigid frame with motorized joints could greatly boost strength and load capacity.

Soft exoskeleton

Fabric, often stretchy, is mated with cables and small motors to deliver a modest assist.



Advantages and disadvantages

Rigid exoskeleton

- Can take **weight off the soldier**, enabling the user to carry heavy equipment.
- **Heavy, and locks users into particular joint movements**. Current designs suffer from slow response.
- **Uses a lot of power**.
- **Exhausting to wear** and has not been shown to boost performance.

Soft exoskeleton

- **Lightweight, energy efficient**, and easy to wear. May boost performance.
- **Doesn't take weight off the soldier**, limiting extra load.
- Current design **isn't tuned to handle running or walking** over uneven ground.

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invented the first HULC. Now, it has contracts to build prototypes for the TALOS. "I think every problem can be solved," he says. "It's just a matter of time."

Researchers are "extensively" investigating tradeoffs between weight, mobility, and endurance, Allen wrote. Although media reports have put the project's budget at $80 million, Allen wrote "we do not know how much TALOS will cost."

When the exoskeleton might appear is also unclear. A timetable that calls for producing a fully functional prototype by 2018 "is on track right now," said Army General Joseph Votel, SOCOM's current leader, at a conference this past January. But he noted that "many significant challenges remain."

UM's Ferris believes the needed technical advances—to shave weight, boost battery performance, and get the machine to move in perfect synchrony with a person—are still far off. "The reality is, they don't understand the engineering and the science," he says of SOCOM. "They don't understand the leap we need to make." And he estimates that TALOS backers will "need a budget of $500 million to make this happen." Such concerns got now-retired Senator Tom Coburn (R–OK) to include the TALOS in the 2014 edition of his annual *Wastebook* of projects he considered government boondoggles.

Scientists at the Natick Army research lab also have expressed concerns. The military still lacks a grasp of the basic biomechanics needed for a successful leg exoskeleton, Gregorczyk and several others concluded in a recent research proposal. The result has been a "best guess" approach that has produced several "poorly functioning devices," including the HULC. They're calling for more fundamental studies to understand how an exoskeleton and human leg interact. "I think Iron Man's too big," Gregorczyk says. "I think we have to start small and see how that works first."

Herr, whose MIT lab has built a small, motorized ankle exoskeleton that broke new ground by showing that it could actually improve walking performance, laments the military's preoccupation with big, bulky designs. "I've been passionately trying to convince the [Department of Defense] to just stop obsessing with that type of architecture," he says.

A MORE PROMISING ALTERNATIVE, some exoskeleton advocates say, can be found in a Cambridge, Massachusetts, lab that looks like a cross between a robotics shop and a fashion design studio. In addition to a treadmill and the usual motors and wiring, engineer Conor Walsh's space at Harvard University features four sewing machines, bins filled with fabric, and a wheeled rack hung with black clothes.

The clothes are emblematic of a different approach to exoskeleton design. Born of a new DARPA program called Warrior Web, it's the antithesis of the TALOS. Rather than building a hefty metal machine that bears the weight of a load—and that can get in the way of normal movement—Walsh and his team are using fabric, flexible cables, and small motors to inject an extra shot of energy into each stride while letting a person move freely. These "soft exosuits" weigh just 9 kilograms, and use just 140 watts of electricity—slightly more than a desktop computer. In theory, the suits could mean soldiers arrive at the end of a long patrol less tired and injury-prone.

To demonstrate how it actually works, Walsh's team let a reporter try out the system. Getting outfitted is a bit like being a model preparing to hit the runway. I pull on a pair of black tights; then Diana Wagner, who's in charge of the fabric side of the project, laces me into the rest of the outfit. Straps wrap corset-tight around my waist, hips, thighs, and calves. Everything has to be snug and form-fitting so that when the motors start pulling, nothing jerks out of place. Sensors tucked into the bootlaces and thigh straps will monitor my legs' movements, telling the machine when to kick in.

After 45 minutes of adjusting, I'm ready to climb on the treadmill. Two engineers lower a backpack adorned with boxes and dangling cables onto my shoulders. They latch the cables into connectors on my waist and legs, and on carbon-fiber spurs that jut from the heels of my Army boots. I pose midstride so that the machine can correctly adjust the cables. Then, Ignacio Galiana, one of the engineers, starts the treadmill. I'm walking at a pace of about 5 kilometers an hour.

My first step is met with a surprisingly abrupt yank on my heel. It lets go and almost immediately my other leg is tugged up and back. I keep my balance and settle into a brisk walk, the tiny electric motors and gears keeping time with a frenetic whirring. They retrieve and release the wires with every step, synced to my pace by microprocessors and the motion sensors. Even after a few minutes, each pull is slightly jarring, a bit like being a marionette with four wires controlling my legs. Am I walking in the suit, or is it walking me?

"We're doing a significant percentage of what your body needs," Galiana explains. "It takes a little bit to get used to these additional forces and be fully relaxed."

After 12 minutes on the treadmill, he turns off the exoskeleton as I keep walking. Something unexpected happens. My legs suddenly feel slower, the boots heavier. There is less pep in my stride.

"That's what we hear often," Galiana says with a grin. "People feel like they are walking in mud."

The suit's benefit, Walsh says, is borne out by the numbers. In a recent test, seven people walking in the suits, and carrying loads equal to 30% of their bodyweight, were on average 7% more efficient than without the suits.

PERFORMING ON A LAB TREADMILL is one thing. But does the soft suit work in the real world?

To answer that question, Walsh and DARPA go to the backwoods of the U.S. Army's Aberdeen Proving Ground, a sprawling 30,000-hectare base north of Baltimore, Maryland. This past summer, on a humid 28°C morning, 21-year-old U.S. Army Specialist Cacciatore (he wouldn't give his first name) goes out for a hike. But this is no normal workout. The only thing standard issue is his close-cropped haircut. And he is trailed by a 12-person entourage of Harvard engineers, Army scientists, and DARPA officials, slipping in the mud and swatting mosquitos.

Before setting out in a soft exosuit and gear totaling 40 kilograms, Cacciatore spends 5 minutes in a lab walking and jumping on a treadmill that measures the force of each step. A facemask helps researchers gauge how much oxygen he is using. On another day, he'll do the same thing, minus the exosuit, to compare the results.

Then, Cacciatore marches at breakneck speed down a muddy path in a tan T-shirt and the black tights, the exosuit's noisy gears giving him a distinctly robotic air. As he tromps along, two following engineers, laptops suspended from their necks, peer at a collage of graphs tracing the machinery's performance.

When Cacciatore reaches a downed tree, he easily steps up and over it. The wires go slack because motion sensors detect something other than regular walking.

Observers are impressed. "I've gotta tell you, it's cool," says Michael LaFiandra, a biomechanics expert and chief of the Dismounted Warrior Branch at the Army Research Laboratory at Aberdeen. "Physical augmentation was kind of a pipe dream. And now it seems like it could be a reality."

Still, there are problems. It's a prototype, after all, not built to withstand battlefield rigors. Twice during the hike, something malfunctions or breaks. Like a pit crew at the Indianapolis 500, the engineers swarm over the soldier, swiftly making repairs.

Later, Walsh won't detail the overall result of the tests. "I can say that it was positive," he allows. The mechanical problems that morning were the only ones in 2 weeks of testing, he says.

Still, Walsh cautions against unrealistic expectations, ticking off a host of challenges. The soft exosuit is programmed for walking, for instance, but not running. It has proven difficult to design a system that kicks in at the right time when someone is traveling over uneven terrain. Some people have an easier time adapting to the suit than others, suggesting any benefit could vary from user to user. And any final version would have to integrate with the many other parts of a military outfit.

The Army's Gregorczyk offers another sobering list of questions that any real-world Iron Man suit—soft or hard—will have to confront. Could using an exoskeleton cause its own set of injuries? Would the performance benefit outweigh the cost? "Say a device reduces the metabolic cost of a soldier carrying a load by 5%," she says. "Does that translate into an operational benefit? Does it mean anything?" ■

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The HULC, a rigid, battery-powered exoskeleton developed by the U.S. military in the late 2000s, failed to deliver predicted performance boosts. Wearing the suit "was a workout," one tester said.

PHOTO: LOCKHEED MARTIN