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MELDING MIND & MACHINE

Instead of using remotes or crutches, future generations of bionic exoskeletons could communicate directly with the nervous system

By Ariel Bleicher

ILLUSTRATIONS BY CLINT FORD

Imagine yourself as a child, standing on the tops of your dad's loafers as he shuffles across the living room. It is exhilarating—being maneuvered like a marionette, his feet moving your feet, his hips swinging your hips. But here is the upshot of walking on someone else's shoes: eventually you would rather do it on your own.

For people who have lost some or all control of their legs, robotic exoskeletons are engineering marvels. In rehabilitation clinics and users' homes, they are getting patients who have lost mobility to spinal cord injury or stroke out of their wheelchairs and moving upright again for short periods. And this renewed locomotion has physical benefits, such as better blood circulation and lower risk of infection.

But for all their virtues, the medical exoskeletons on the market today have some clear limitations. Most models, for example, require patients to use crutches and allow only a limited range of motion. Engineers expect basic features such as agility and balance will improve with more sensors and more sophisticated control algorithms. The biggest advances, though, may come from making better use of patients' own abilities.

Several research groups are now working on a next generation of exoskeletons that electrically stimulate patients' muscles to partially power the robotic brace. Further in the future, new devices that decode brain activity, known as brain-machine interfaces, or BMIs, could let patients control their cyborg legs with their mind. Tomorrow's exoskeleton may do more than move a pair of limbs. By creating a dialogue with the nervous system, it could become an integral part of the person who uses it.

The Body Electric

In the 1960s doctors began working with engineers to outfit mechanical braces with wearable electrodes, known as functional electrical stimulation (FES) systems, to aid in walking. The first of these contraptions, called hybrids, sent a gentle jolt through the calf to the peroneal nerve, which flexed the ankle, preventing patients from dragging their toes, a common symptom of stroke and multiple sclerosis. By the 1980s volunteers with spinal cord injuries were testing hybridized leg orthotics. These specialized braces used finger switches wired to strategically placed electrodes to contract the quadriceps and hamstrings, facilitating steps.

These early hybrids, however, had one big shortcoming. After a spinal cord injury, muscles shrink and weaken. Slow-twitch fibers, which enable sustained movements such as walking, morph into fast-twitch fibers, which provide instant force but become fatigued quickly. Patients could not power such a device very long before their muscles needed a rest. "Gravity always wins," says Ronald Triolo, executive director of the Advanced Platform Technology Center at the U.S. Department of Veterans Affairs.

Robotic exoskeletons could offer a solution. Triolo and other researchers are now incorporating FES into exoskeletons in hopes that they can coordinate with patients' muscles to share some of the burden. For example, Triolo's team is developing a prototype hybrid that requires implanting electrodes in the body to more precisely activate individual muscles by accessing deep nerves such as those that control the hip flexors. The scientists have found that contracting these muscles can lift the knee high enough for patients to climb stairs, but they can mount only a few steps before tiring. With a little extra push from the robot, they can ascend an entire staircase.

And there are unique advantages to exoskeletons with this hybrid design. Compared with traditional exoskeletons, these new devices require a user's body to do more work. "If you use a muscle instead of a motor for some movements, you can get away with much smaller motors and potentially have a smaller, lighter apparatus," Triolo says, which would make exoskeletons easier to transport and extend their battery life.

Exercise is another perk. Putting deconditioned muscles back to work builds strength and tone and increases metabolism, improving overall health. Many experts believe hybrid exoskeletons could help regenerate neural connections that were damaged or weakened by an injury or stroke. "For the neural system to recover, you need neurons firing," says Michael Goldfarb, an engineering professor at Vanderbilt University whose laboratory developed the technology behind the exoskeleton Indego, which U.S. manufacturing giant Parker Hannifin plans to release later this year. The company is also developing models with FES capability and expects to test these hybrids in clinics in 2016.

For some paraplegics, no amount of stimulation will get the muscles pumping again. But for the thousands of wheelchair-bound people who might benefit, hybrid exoskeletons could provide a safe way of learning to walk more independently. Goldfarb envisions these machines teaching locomotion like a coach spotting a gymnast. "As the muscles do more and more, the robot does less and less," he says. Some stroke patients, he predicts, may even recover well enough to "give the device back."

The Mind in Motion

The next frontier is the brain. Because exoskeletons today are operated physically, via manual controls or body positions, they demand a great deal of focused attention. Users cannot sip a cup of coffee, for example, or hold a lover's hand as they stroll down the street. A BMI could free the hands for multitasking while allowing more dexterous movements.

In a pioneering experiment with monkeys in 1969, physiologist Eberhard Fetz of the University of Washington showed it was possible to use electrical signals in the brain to control something outside the body. By implanting electrodes in monkeys' motor cortex, the brain region that governs voluntary movement, Fetz was able to record the activity of individual neurons. When these cells randomly fired at a certain rate, a monitor pinged, and the animals, which were strapped to a chair, got a treat. In just minutes, the monkeys learned to tweak their brain activity to ping the monitor whenever they pleased, essentially producing the sound—and a snack—with their mind alone.

FAST FACTS

THE ROBOTIC WALKING COACH

1. Existing exoskeleton technology can help people with impaired mobility, but it has significant limitations.
2. Functional electrical stimulation systems, which use gentle current to coax muscles into action, could enable lighter and more restorative bionic aids.
3. In the future, exoskeletons could communicate directly with the brain via implants or a sophisticated net of electrodes on the scalp.

CURRENT TECHNOLOGY

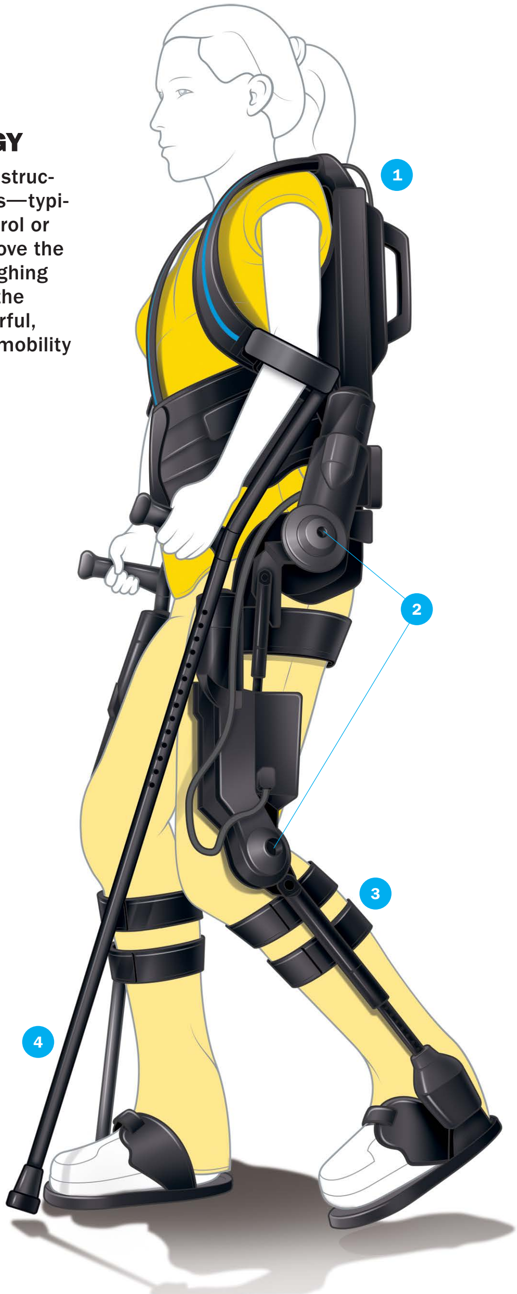
Today's exoskeletons provide structural support and use robotics—typically guided by a remote control or shifts in body position—to move the device and user forward. Weighing between 22 and 50 pounds, the equipment is heavy but powerful, enabling people with limited mobility to stand upright and walk.

1. A backpack contains a battery and computer, which controls the robot.

2. Electric motors at the hips and knees move the upper and lower legs.

3. Leg braces support the user and house sensors that provide feedback on joint position.

4. Crutches help with balance and in some cases include buttons to direct the exoskeleton.



By creating a dialogue with the nervous system, tomorrow's exoskeleton could be an intimate part of the person who uses it.

Using implants in rodents, monkeys and humans, researchers have since built more sophisticated BMIs to operate a cursor on a screen or a robotic limb. In a 2012 study, scientists led by Leigh R. Hochberg of Brown University taught two quadriplegic individuals to reach for and grasp objects with a robot arm by using only their thoughts. In each patient's motor cortex, a 96-electrode array the size of a baby aspirin recorded the chattering of hundreds of neurons. Using a mathematical model called a decoder, the researchers then translated these signals into machine commands, such as force, velocity and position—in much the same way that the spinal cord transforms the brain's output into a flutter of muscle contractions.

There are, however, problems with this BMI scheme. Although an implanted array gives the most fine-grained account of one's state of mind, it can invite infections and rarely lasts for more than a couple of years. That is because the brain attacks the device as a foreign invader, enveloping it in proteins that dampen the neural signals.

These drawbacks have led some researchers to investigate BMIs that use electroencephalography (EEG) systems, which record rhythmic activity across the entire brain through a net of electrodes on the scalp. Until recently, scientists believed EEG signals were too weak and noisy to use for controlling an exoskeleton. But a series of studies in 2010 suggested that, in fact, an EEG-based BMI might be able to decipher intended hand and leg motions with surprising accuracy. "We're still figuring out the limits of EEG," says José L. Contreras-Vidal, a neuroengineer at the University of Houston who led the studies. He is currently testing an early prototype called NeuroRex, an EEG-equipped exoskeleton that allows patients to initiate steps just by thinking about walking.

At Duke University, Miguel A. L. Nicolelis has undertaken a similar endeavor called Walk Again. The project made

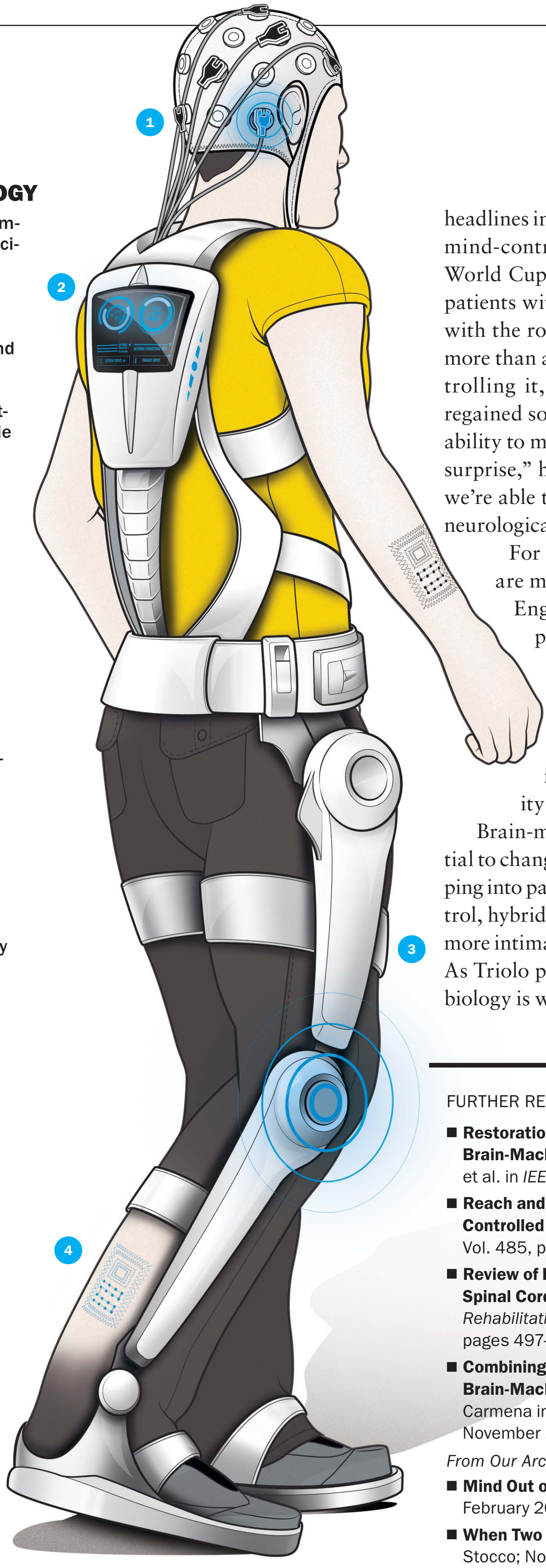
THE AUTHOR

ARIEL BLEICHER is a freelance science journalist in New York City. She has written for *Scientific American* and *IEEE Spectrum,* among other publications.

headlines in 2014, when a 29-year-old paraplegic used a mind-controlled exoskeleton to literally kick off the World Cup in Brazil. Since then, Nicolelis says, eight patients with spinal cord injuries have been practicing with the robot in his lab two to three days a week for more than a year. They have gotten much better at controlling it, he reports. Remarkably, they have also regained some sense of touch and, in several cases, the ability to make small leg movements. “This was a great surprise,” he says. “It seems we’re at a threshold where we’re able to not only restore mobility but also induce neurological recovery.”

For the moment, brain-controlled exoskeletons are most likely decades away from common use. Engineers must first show they can make implants safe and durable or else use EEG signals from the scalp to direct more diverse skills, such as turning and ascending stairs. They must also ensure that real-world distractions, such as talking or eating, will not interfere with the decoder’s ability to interpret a user’s intentions.

Brain-machine interfaces ultimately have the potential to change how an exoskeleton serves its user. By tapping into patients’ natural systems of movement and control, hybrid and brain-directed assistants could become more intimately bound to the minds and bodies of users. As Triolo puts it, “working with biology instead of for biology is where the future is going.” **M**



FUTURE TECHNOLOGY

This artist’s rendering combines the same core principles of current exoskeleton devices with a few critical innovations. The lighter design removes cumbersome crutches and remotes, relying on the user’s brain to direct the equipment. Electronic tattoos could deliver a gentle vibration to the forearm or leg—depending on an individual’s existing sensitivities—offering additional feedback as a person walks.

1 An electrode cap records brain activity, allowing the user’s mind to directly issue commands to the machinery.

2 A computer converts brain signals into instructions for movement.

3 Motorized leg braces electrically stimulate muscles and assist in walking.

4 Electronic tattoos vibrate to provide sensory feedback, enabling people who lack other cues as the result of injury to still “feel” their movement through space and even the texture of the terrains they travel over.

FURTHER READING

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