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FEATURES

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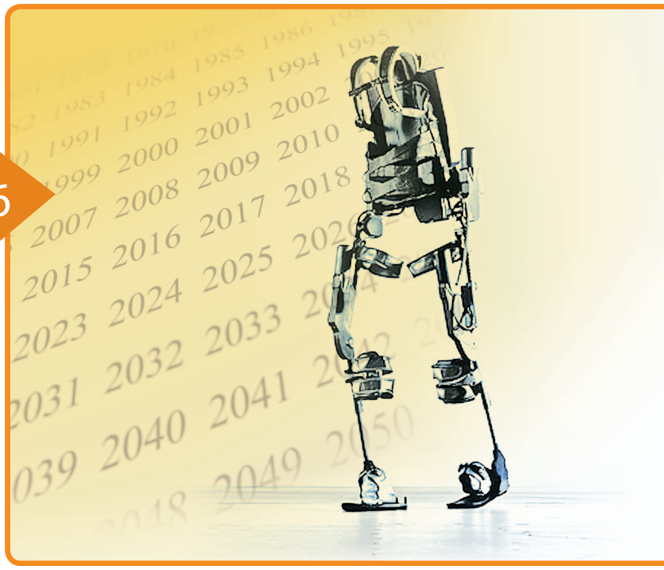

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COLUMNS & DEPARTMENTS

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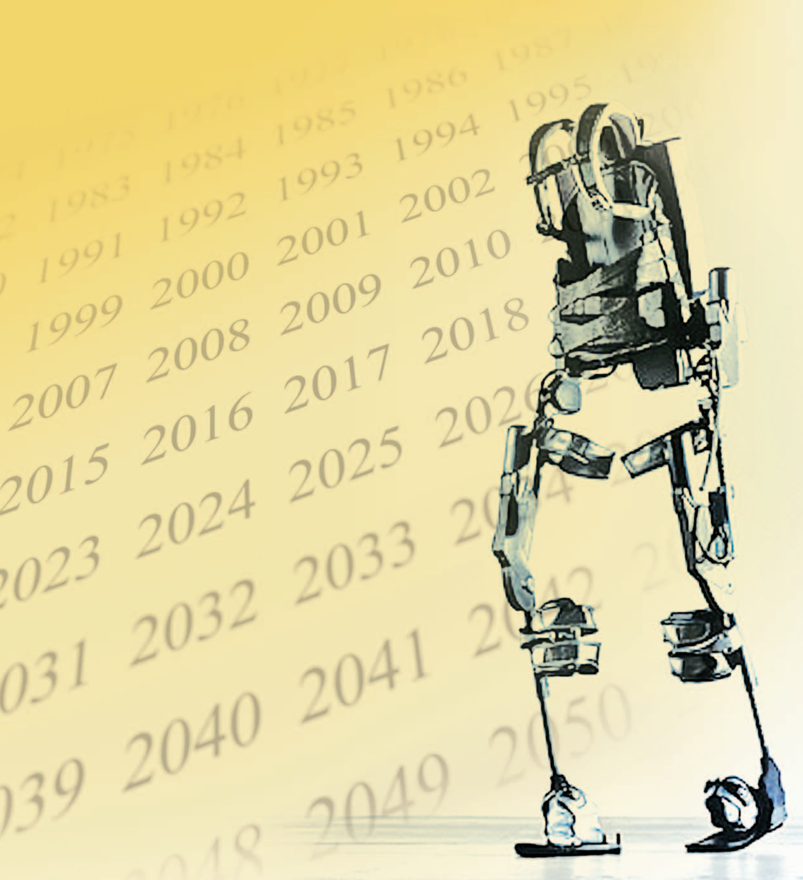

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The Next Generation of Exoskeletons

By Leslie Mertz

Many researchers and engineers are busy in their laboratories working on devices that will bring mobility to people who have lost function in the lower body due to an accident, stroke, multiple sclerosis, or other disorders. "Several pretty sophisticated exoskeletons are already on the market now, and they are all similar to each other in terms of technologies, but we're not ready to replace the wheelchair yet," said exoskeleton developer Homayoon "Kaz" Kazerooni, Ph.D., professor of mechanical engineering at the University of California (UC) at Berkeley. "Eventually, we will have devices that are used by individuals on a daily basis to replace wheelchairs but not with the existing technology. We're at the beginning of a much bigger era in exoskeletons."

Lighter, Cheaper Devices Are in the Works

Why Now?

Exoskeletons with names such as ReWalk, Ekso, and HAL, which stands for hybrid-assistive limb, are the new talk of the town, and there's a reason why they are showing up now. "We have seen some significant improvements in robotics technology and mechatronics technology over the last five years, and they have enabled this," said Michael Goldfarb, Ph.D., H. Fort Flowers professor of mechanical engineering at Vanderbilt University and a designer of Vanderbilt exoskeleton. Some of the major stepping stones in the rise of the exoskeletons include the rare-earth magnet brushless motors, the overall quality and capability of microprocessors, and the high-power electronics that drive the motors in ultracompact devices.

"In addition, the U.S. government invested a lot of money in microelectromechanical systems (MEMS) and, in particular, multiaxis accelerometers and gyroscopes that we're incorporating into exoskeletons. We're using high-quality MEMS sensors that only became available a couple of years ago," Goldfarb said. The automobile industry's hybrid and electric-car programs pitched in as well, by helping advance battery development. "There's been a confluence of a lot of important technologies that were not available a decade ago, so exoskeletons were not possible until now."

Beyond the new technologies, medical exoskeletons, for at least one researcher, also represent an almost-intuitive expansion of his research. Kazerooni and his group began working in this field almost two decades ago when they started developing systems to help soldiers carry loads. He was one of the founders of Berkeley ExoWorks, later known as Berkeley Bionics and now called Ekso Bionics, and his group developed several exoskeletons, including

- the ExoHiker—completed in 2005, it allows users to carry up to 200 lb on their backs while hiking and even running over different terrains

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- the ExoClimber—also completed in 2005, it combines the capabilities of the ExoHiker with the capability to quickly climb stairs and steep slopes
- the Human Universal Load Carrier (HULC)—unveiled in 2008, HULC permits users to carry loads of up to 200 lb for sustained periods. Lockheed Martin Corporation licensed HULC in 2009 for further military development.

Through that work, Kazerooni and his research group refined exoskeleton design and control algorithms. "It was a natural progression from military to medical for us," he said. "Once we developed HULC and we realized that we were able to move a soldier back and forth really fast and have a load on him and that the technology was successful, then we gained a high level of confidence to move forward for a large community of people who have disabilities and who need these machines."

Kazerooni and Ekso Bionics went on to develop the Ekso exoskeleton (Figure 1), a device to help paraplegic individuals walk. The Ekso exoskeleton made the news recently when it delivered its first commercial unit in February 2012 to Craig Hospital in Denver, Colorado. Now that the Ekso and a few other exoskeletons are entering the marketplace or being introduced into clinics for further evaluation, Kazerooni has left Ekso Bionics and returned to his UC lab to begin work on the next generation of exoskeletons.

The stroke patients use the exoskeleton as a tool to help regain their limb control.

Just as the cars, airplanes, and cell phones of years past have evolved over time into vehicles and devices that are far improved, exoskeletons will do the same and hopefully soon, Kazerooni said. "I think what's out there is good for now, but they're not quite cutting it. They aren't quite sufficient. The biggest problem is that the existing exoskeleton systems are extremely expensive, and people with mobility disorders can't afford them. That to me is a showstopper, so I'm back to the university to create a more accessible device for a large number of people with mobility disorders."

"I have a sense of rush now, because what we're developing is not a telephone, it's not an airplane, it's not a car. It's a necessity for a person," he added, "We need to give the ability to walk and be mobile to the large number of people, especially children, who are confined to wheelchairs."

Good Things, Small Packages

To Kazerooni and many other exoskeleton developers, size matters in terms of devices for mobility disorders, the smaller the better: less hardware, fewer bells and whistles, and lower cost. When it comes to robotics and people, you want limited hardware," said Kazerooni, a self-described minimalist designer. "The machines must be trivial in comparison to the person. We must place more emphasis on the software and the controller and less on the hardware. We don't want to give the image of wearing an Iron Man suit."

He envisions an exoskeleton that covers the basic movements, and nothing more. "I'm talking about essential functionality, such as standing up from a chair. That's essential because it allows a person to go to work. You can go to work, sit in a computer chair, and stand up. That, to me, is a huge deal. If a person

EKSO BIONICS.

FIGURE 1 Ekso Bionics delivered its first commercial bionic exoskeleton in February to Craig Hospital in Denver.

can't do that by themselves, it's not independence." Kazerooni counts other crucial movements as getting on and sitting on a bus, and stepping up on and down from a curb. "I'm thinking of basic, but enabling maneuvers rather than show-off-type movements. They don't have to go backward, they don't have to go down the sidewalk, they don't have to climb ladders or stairs. Those kinds of movements are a little more sophisticated, and they will come in the future. For now, I'm looking at a handful of fateful maneuvers, ones that actually mean that a person is independent. We need a machine to do that faithfully and without any danger to the person. And it has to be of low cost."

Cost has become the main focus of his research group because the currently available exoskeletons are out of financial reach for most people who are disabled, he said, noting that they often face financial struggles stemming from limited

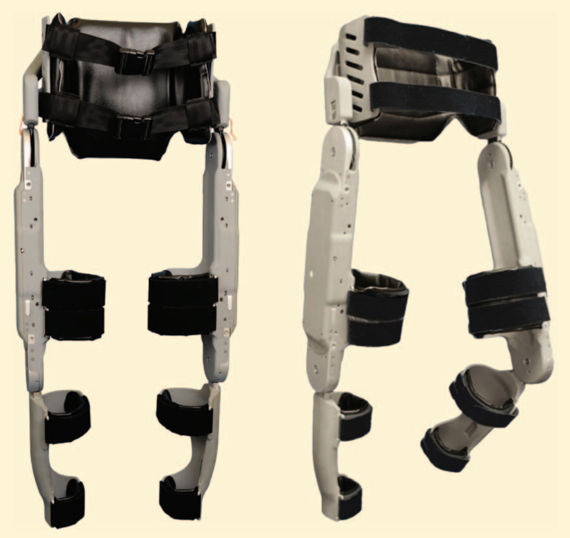

FIGURE 2 Vanderbilt University's exoskeleton extends from the hip to the calf and incorporates all of the robotic controls, customized electronics, and batteries within the device, thereby eliminating the backpack used in many other exoskeletons. (a) Front view and (b) side view. (Photo courtesy of Ryan Farris and Hugo Quintero, Center for Intelligent Mechatronics at Vanderbilt.)

employment and educational opportunities. "A large number of these people cannot pay US$100,000 or US$130,000 to buy an exoskeleton, and insurance won't pay for it, so price is a big issue."

To cut costs, Kazerooni said that his research group is leaving no stone unturned. "Everything adds up. We're looking at the engineering, as well as the manufacturing and delivery, because they are intertwined." He is happy with his group's progress so far. "We have a strong team, and we already have innovations. For example, we have a machine in our lab that probably costs no more than US$10,000 to make, and we have a friend of mine who is paraplegic and is walking with it. So we're almost there." Bridging the gulf between this prototype and a marketable product, however, will require a year or two of additional work and, probably, several iterations, plus the support of investors or the government.

"I believe we can make a US$10,000 exoskeleton," Kazerooni said. "No one tells me we cannot do it, so I had no choice except to return to my lab with my students and my staff and to try to come up with a new set of technologies to make that feasible. Once these people become mobile and more independent, you can imagine how many doors will open for them. It will be game changing if we can do that."

FIGURE 3 With the Vanderbilt exoskeleton, users can sit, stand, walk, and both ascend and descend stairs and slopes. (Photo courtesy of Ryan Farris and Hugo Quintero, Center for Intelligent Mechatronics at Vanderbilt.)

Lightweight, Minimalist

In his Vanderbilt University laboratory, Goldfarb and his research group are constructing their own version of a minimalist exoskeleton that permits basic functions that Kazerooni described and walking up- and downstairs and slopes. "Our exoskeleton extends from just above the waist to midway through the shank or calf. This is different from some of the other emerging devices that continue down under the person's feet," he said (Figures 2 and 3).

They selected the hip-to-calf design for a couple of reasons. Weight was one. "In the automotive world, they say that if you can take a pound out of a car, then you've actually taken out 3 lb because by removing that initial 1 lb of payload, you can make the engine smaller because it's not moving around as much weight, and you can make the transmission smaller because the stresses aren't as high, and so on," Goldfarb said. "You get this multiplicative savings. The same thing happens with exoskeletons." Their device comes in at just 27 lb. This is compared to other currently available exoskeletons that weigh 40–45 lb.

Another reason for Vanderbilt's hip-to-calf design was that they wanted the person's body weight to carry through his or her own skeleton to the floor rather than transmitting the body weight through a longer exoskeleton that extends under the foot, Goldfarb said. "Spinal cord-injured persons have very high instances of osteoporosis, which is why doctors recommend they use a standing frame for a certain period of time every day. By having the exoskeleton end at midcalf, we can put stress on the bones so that they can stay healthy."

The Vanderbilt exoskeleton includes motors at the hip and knee joints and incorporates all of the robotic controls, customized electronics, and batteries within the device. "The machinery is in the two thighs, the battery is in the hip piece, and it all talks to one another through a communication circuit within the device. So we also didn't need the backpack that some of the other devices have," Goldfarb said. This design puts most of the weight of the device at the hip and eliminates any weight from the shoulders.

The Vanderbilt exoskeleton is modular, with three pieces that snap together or apart quickly without the need for tools, Goldfarb said (Figure 4). "We wanted a person with a spinal cord injury to carry the exoskeleton in a case that straps onto the back of a wheelchair. When they want to use it, they can simply take it out, put it on, get up, and go."

As with other exoskeletons, the Vanderbilt device requires the subject to use a stability aid. "Our subjects use forearm crutches," Goldfarb said. "Some people ask if it's possible to get rid of the crutches, and I think that at this moment, it's not possible." One reason is that the patient controls the exoskeleton's movements by leaning slightly forward or backward, and because they're paralyzed, the crutches provide the stability to safely do that, he explained.

"With our exoskeleton, if you're sitting and you want to stand, you first pull up on one leg and then the other, and that tells the device to put your feet under you, which is necessary for standing. Then you push up a little bit to move your thighs slightly. That's enough to tell the machine that you want to stand,"

FIGURE 4 The Vanderbilt exoskeleton is a three-piece, modular device that quickly—and without tools—snaps on and off. (Photo courtesy of Ryan Farris and Hugo Quintero, Center for Intelligent Mechatronics at Vanderbilt.)

Goldfarb described. "Once you're standing, if you lean forward, it means you want to walk, and you lean forward to a certain extent to tell the device to take the next step." Other leaning movements tell the machine to stop or sit.

"It's similar to the way the Segway works. Both are sensing what certain tilts mean, and what holding certain tilts mean. Of course, each device interprets the tilts differently, but we're essentially using the same set of sensors." Goldfarb's research group works with both physical therapists who specialize in spinal cord injuries and with individuals who have complete spinal cord injuries and lower-body paralysis. Because of the subjects' lack of sensation, the Vanderbilt research group had to ensure that the exoskeletons provided unfailingly dependable movements, especially when the users were walking. "Otherwise, the subjects would have to stare down at their feet all the time to know where they are. We had to develop a device such that the person could trigger the next step and know where things were going to be," he said. That took some time. "We ended up doing things iteratively: tweaking the controller, sometimes changing the mechanical design. We needed to fix what needed to be fixed to create a gait that is consistent. That's particularly important for this population."

One of the unexpected issues that arose involved the subjects' skin. "Because they don't have sensation, something can rub up against them and they won't know it until they see their skin bleeding. Also, part of the autonomic nervous system doesn't work anymore, so their skin can be highly sensitive," Goldfarb said. "That meant that we had to make sure that the device didn't contact any bony points, which would cause too much pressure on the skin." With early versions of the device, subjects could only wear the exoskeleton for 30 min, and then if needed, a 30- to 45-min break for the skin to recover. He said, "After a number of design revisions, we're at the point now where our subjects can wear it pretty much all day, and they have no skin problems at all."

Goldfarb is pleased with the progress so far, and licensing discussions are in progress with a few companies to bring the exoskeleton to market. "I was in earshot when one of our subjects said that this is the closest thing to walking that he's experienced since his injury nine years ago. You can see from the videos on our Web site [1] that it's clearly not dynamic walking, but he feels like it's walking, so we must be getting something right."

Exoskeletons for Stroke Recovery

Exoskeletons aren't just for individuals who are paraplegic due to a spinal-cord injury. Several research groups are working on new devices to help treat the effects of a stroke. Rather than wearing the exoskeletons so that they can walk, the stroke patients use the exoskeleton as a tool to help regain their limb control.

In stroke, brain cells die partly, and this results in loss of motor control on the opposite side of the body. Unlike a severely damaged spinal cord, which most medical professionals believe is a permanent injury, the brain has the capacity to recover from stroke damage as part of an inherent neural rewiring mechanism known as brain plasticity. The brain responds to physical therapy that provides repetitive movements of the affected arm or leg by learning and regaining motor functions. Those movements trigger the brain to essentially migrate lost motor control function from the damaged area of the brain to a healthy area. Exoskeletons are one way to help generate those repetitive movements and possibly promote a faster, better, and long-lasting recovery.

FIGURE 5 Prof. Jacob Rosen wearing the two-arm exoskeleton with seven degrees of freedom each. The system allows the user to reach 95% of the natural workspace of the human arm and provides assistance and guidance with forces that are similar to the forces produced by the muscles of a healthy individual. The system has applications in haptics (providing force feedback in virtual reality), teleoperation (controlling a robotic system from a distance). It is currently tested in the context of stroke rehabilitation utilizing a bilateral mirror-image mode of operation.

Study results conducted at UCSF with stroke patients show that the exoskeletons are making a difference, according to Jacob Rosen, Ph.D., professor in the Department of Computer Engineering at UC at Santa Cruz and director of the Bionics Lab. He and his students developed EXO-UL7, a system that incorporates two wearable exoskeleton arms (Figure 5) operating in "bilateral mirror-image mode." This copies the natural arm motion from

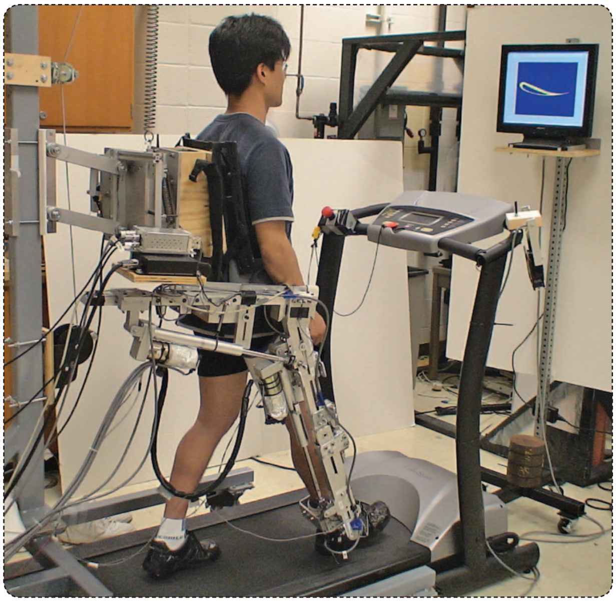

FIGURE 6 Prof. Sunil Agrawal's group at the University of Delaware developed the GBO, which is a completely motor- and electronics-free passive exoskeleton [4]. (Photo courtesy of Prof. Sunil Agrawal.)

the healthy side of the body to control the disabled arm in a similar fashion.

According to a theory in neuroscience, he explained, mirror-image movements are the fundamental way of moving, and therefore may be utilized in recovering lost motor control through brain plasticity following the incident of a stroke. “Mirror-image movement is an important rehabilitation strategy, because the arm as a redundant mechanism can adopt infinite arm configurations when you are, for instance, reaching out to a certain point in space,” he said. “How the brain is selecting one of these configurations out of essentially infinite solutions is still an open research question. However, by utilizing bilateral mirror-image mode of operation with two exoskeleton arms, the solution is given to the operator because the brain already picked the solution for the healthy side, and the system just mirrors it into the disabled side.”

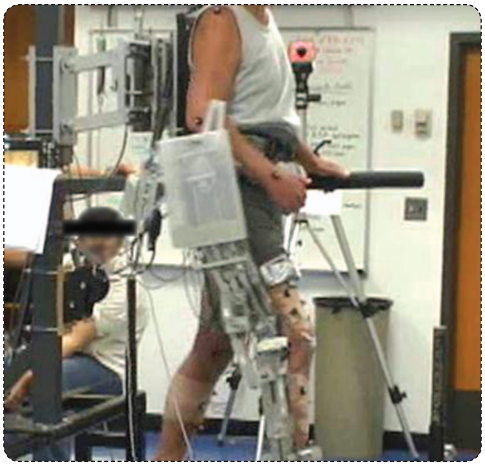

FIGURE 7 Prof. Agrawal’s research group also developed two versions of a the robot-controlled ALEX, which is pictured here. ALEX and the passive GBO are designed to help stroke patients regain the ability to walk [2]. (Photo courtesy of Prof. Sunil Agrawal.)

The coupling between the left and the right sides of the body can be controlled and reduced over time as the patient regains independent motor control over the disabled side of the body as part of the treatment, he said. Given the positive initial indications following the experiment with stroke patients in a clinical setting at UCSF, he said, a commercialization effort is under way to make the system available to the public as an advanced therapeutic device for stroke patients as well as for additional patients suffering neuromuscular disorders who require physical therapy and for treating patients following orthopedic joint replacement and physical trauma.

The biggest problem is that the existing exoskeleton systems are extremely expensive, and people with mobility disorders can’t afford them.

Although the standard of care for stroke patients includes only three to six months of therapy, his research group has shown that the two-arms exoskeleton system can help stroke patients continue to improve long after that short recovery window. Rosen said, “We work with people who had poststroke at one to ten years, and even after such a long time, the brain is still plastic, meaning that the brain is still responding to treatment.”

Sunil Agrawal, Ph.D., professor in the Department of Mechanical Engineering at the University of Delaware, is seeing similar results with his research group’s exoskeletons [2], [3]. They developed the gravity balancing leg orthosis (GBO), which is a completely motor- and electronics-free passive exoskeleton as well as two versions of an active leg exoskeleton called *ALEX I* and *ALEX II*, which are controlled by a robot (Figures 6 and 7).

The GBO is an aluminum, bracelike scaffold, the sections of which are connected by springs [3]. By adjusting the springs, the device can help the patient lift the leg, which is important early in stroke therapy, Agrawal explained. “With this machine, we can selectively modulate how much gravity force the leg is feeling. Our training paradigm is that we start off by providing 100% gravity force, which means that you can lift your leg off the ground without applying any muscle exertion and you walk with that condition. Over the next six weeks of therapy, we calibrate the position of the springs and the level of gravity assistance from 100% to 75% to 50% and so on, so that by the end of the training period, you are walking with normal Earth gravity.” Results of a study with paradigm, which was tested with a stroke patient, have been presented in *Journal of Neurological Physical Therapy* [4].

ALEX I and II are similar to the GBO in that the patient wears them while walking on a treadmill in a clinical setting, and they modulate assistive/resistive forces on the leg using an assist-as-needed paradigm similar to that used by a physical therapist during training [2]. ALEX I and II, however, have motors, sensors, and real-time control feedback. “They both have their roles to play in this field. The GBO is a cheaper but still effective device, while ALEX provides precise control over the external force provided from the device onto the patient. When somebody has a stroke and begins therapy, perhaps that would be a good time to use a passive device, such as the GBO. As time goes on, they could then continue with an active device, such as ALEX.”

Both the GBO and ALEX are patented, and Agrawal said his research group and the university have begun partnering with hospitals to hopefully place the devices in clinical settings. They also hope to commercialize them soon. In the meantime, a third generation of ALEX, ALEX III, is in fabrication. “It’s a bilateral device instead of a one-leg device because we also want to study how adaptations happen on the healthy leg when you train the affected leg,” he commented.

Using the exoskeletons, Agrawal’s group has conducted studies on mobility recovery in people who have three years poststroke. “These are people who got some medical attention for the first six months after their stroke but who are now living at home and are just coping with the residual effects of their stroke,” he said. “Even with these patients, we are able to bring them into our laboratory and help them improve their walking.”

Currently, Agrawal is continuing a study of stroke patients to learn how long the positive effects of the exoskeleton persist compared with the treadmill training that is often prescribed. In the traditional training, a harness supports the patient while he or she walks on a treadmill. In exoskeleton training, the patient wears the device while walking on the treadmill. In this study protocol, Agrawal’s group conducts six weeks of training on individuals who have had a stroke, and then follows up by evaluation of their gait at one-, three-, and six-month posttraining. According to Agrawal, "On our subjects, we have been able to show that they are able to improve their walking functions in terms of speed, which almost doubled, their range of motion, the support (of their body weight), and symmetry of their gait when using the exoskeleton. And they were able to retain much of these improvements three months after treatment, six months afterward, and even more."

Symmetry of gait is of special importance to stroke recovery because the patient usually has only one affected side, which can promote a persistent, uneven walking pattern.

Symmetry of gait is of special importance to stroke recovery because the patient usually has only one affected side, which can promote a persistent, uneven walking pattern. "They can't exert forces to the foot of the affected leg, so they balance everything on the good side and put little emphasis on the bad side. They look as if they are hobbling. Our studies with the robot exoskeleton have shown that they are able to put more weight on their affected leg during training, and they are able to retain some of this even six months after training."

How long should the therapy continue to the most benefit? No one knows, Rosen said. "The brain is still a mystery, and the disabled brain even more so. Nobody can tell how much therapy a patient needs or when to expect change." Quite possibly, he said, therapy may be a life-time endeavor. "Just as we keep going to the gym although we have developed muscles and we are healthy, maybe these stroke patients would benefit from going to a facility for the rest of their lives to maintain or to improve their motor-control skills. We just don't know yet."

A Desperate Need

Whether the exoskeletons are used to treat spinal cord injury, stroke-induced disability, or some other mobility disorder, researchers agree that one thing is desperately needed: studies to prove their health benefits. "As attractive as exoskeletons seem, especially to people who are paraplegic, and as much as our subjects want them, quality of life is not a consideration for insurance coverage," Goldfarb said from his lab at Vanderbilt. "We need studies that clearly demonstrate how mobility helps patients do better healthwise."

UC's Kazerooni added, "Studies on health benefit require time and they require large populations. To test the health benefits of using an exoskeleton for two hours a day for five years, for instance, requires both a test group and a control group, and then studies on whether secondary diseases have been postponed or decreased in the test group, or whether other health improvements have occurred over that period. Those are big undertakings, and I'm not aware of any structured studies that are underway."

That certainly doesn't mean such studies are beyond the realm of possibility, Goldfarb said. He believes that exoskeletons and exoskeleton-based therapies will eventually be shown to lessen osteoporosis, muscle spasticity, and circulatory problems among people with complete spinal cord injury and that those studies will help them one day to become insurance-covered treatments. "I hope to graduate to those types of studies eventually. For now, though, we are still in the middle of the development phase. For sure, however, the next study we propose will be a health-benefit study, and since we're engineers and not clinicians, we will have to partner with others to get it done."

Goldfarb again emphasized the importance of health-benefit testing to the future of exoskeletons and new mobility tools. "We've seen several exoskeletons emerge recently, and in the coming decade, I think a lot of these will get traction in the health-care market because technologically they're ready. The one caveat that's important is that we have to establish the right reimbursement models because while the technology is there and the demand is obviously there, that is not sufficient." He added, "If we can get the reimbursement models in place, you'll see this start to have more and more of a role in this health-care industry and, in particular, in providing therapy for persons with locomotor deficiencies."

What the Future Holds

As these research examples are clear, within the next decade, it is likely that exoskeletons will have the potential to benefit those people who

- have a complete spinal cord injury and lower-body paralysis
- have an incomplete spinal cord injury and significant lower-body locomotor deficit
- are recovering from a stroke that has affected their mobility
- have multiple sclerosis or another disorder that affects their ability to walk.

Although they aren't ready to replace the wheelchair yet, they are on their way, said Kazerooni. "I can't predict the year it will happen. I can't tell what the future is, but I just know that our group is working very fast, and other groups are doing the same thing. Pretty soon, we will have a minimal device that is affordable and allows these people to walk."

Leslie Mertz (lmertz@nasw.org) *is a freelance science, medical, and technical writer, author, and educator living in northern Michigan.*

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