Electricity Flexes **Muscles**

Now even paraplegics can ride a bike – thanks to functional electrical stimulation, a method that takes the place of the nerve signals of the brain. At the **Max Planck Institute for Dynamics of Complex Technical Systems** in Magdeburg, **Thomas Schauer** is working on a sophisticated control system for this technology, which also helps get stroke patients quickly back on their feet.

TEXT **TIM SCHRÖDER**

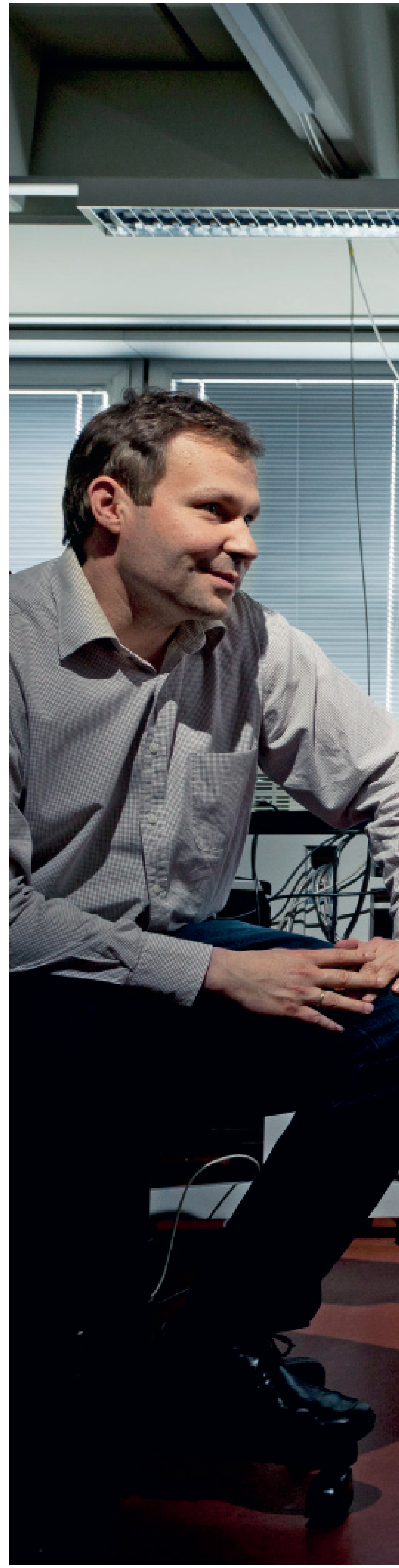
An electric current gives a strange, tingling sensation when it flows into your skin, as if mineral water were bubbling in your forearm. It is odd to see the flat electrode on your skin and not know how strong those pins and needles will become; but the anticipated prickling stays away. It doesn't take much electricity to get the muscles moving: first the fingers lift, then the heel of the hand, and finally the whole hand hovers over the tabletop. It falls and rises again with the ebb and swell of the current, apparently of its own accord, rather spookily.

Thomas Schauer is a master of the art of fine-tuned muscular remote control. He gets paraplegics cycling and helps stroke patients learn to walk again. His laboratory contains a huge tricycle for adults, alongside an ergometer with wires trailing out of it. These end in small gray boxes with control dials, and in electrodes for sticking to the skin like band-aids.

Schauer's specialty is electrical stimulation. He regularly shows his visitors what that is by demonstrating the hovering-hand experiment. Of course, electrical stimulation has been around for a while. As early as the 1960s, scientists tried to help stroke patients walk using small bursts of current. Until quite recently, however, it remained a simple "on/off" technique. Who would have thought that electrical stimulation could be adapted for individual patients, or adjusted for specific situations? Yet this is exactly what Schauer does, using an ingenious computer control unit.

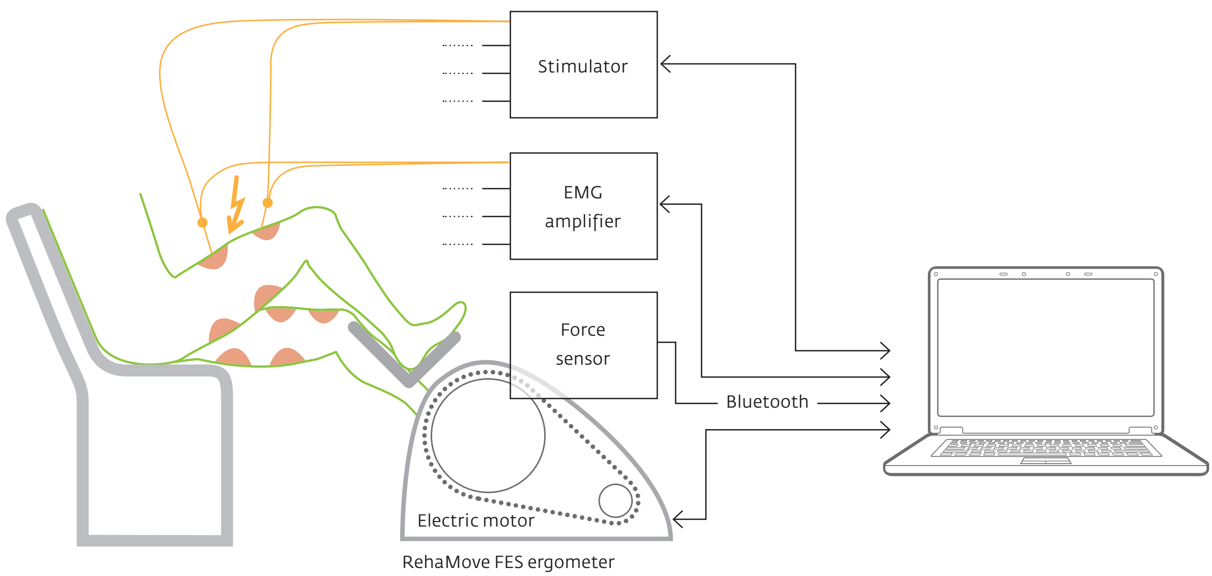
MUSCLES AS COMPONENTS OF TECHNICAL CONTROL LOOPS

The technique developed by the electrical engineer, who specializes in control engineering, doesn't use muscle stimulation as a blunt instrument. Instead, the computer measures how strongly the muscle responds, how powerfully the leg swings or the foot presses against the floor. Then the system reacts: it adjusts the next electric pulses to the muscle effort to generate a flowing movement. Schauer makes the muscle a component of a technical control loop.



Electronic mobility aids: Patients left with paralysis following a spinal injury or stroke can be helped to perform many movements through functional electrical stimulation. Thomas Schauer, Thomas Brunsch and Jörg Raisch demonstrate the systems that can be used to raise an arm or foot.

Photo: Sven Döring



above | How functional electrical stimulation helps patients ride a bike: The ingenious control system uses data from the electromyograph (EMG) and force sensors to determine how much stimulation the muscles need. If necessary, an electric motor helps the patients pedal.

right | On a recumbent tricycle, Christian Klauer, Thomas Seel and Thomas Schauer (from left) try out the system, which comprises sensors, stimulators and a control unit and makes fitness training for paraplegics a reality.

Together with his boss, Jörg Raisch, whose control engineering research group is divided between Magdeburg's Max Planck Institute for Dynamics of Complex Technical Systems and the Technische Universität Berlin, he has made great advances in recent years.

It all began with the idea of teaching paraplegics to ride a bike. At that time, a professor had summoned Schauer to Glasgow University for his doctoral studies, to a new research group focusing on "functional electrical stimulation." In paraplegics, the conduction of nerve impulses to the muscles is interrupted; the muscles and their corresponding nerves still work, but their connection to the brain is severed. "Back then, we felt that it ought to be possible to generate a harmonious pedaling motion using appropriate control engineering," recalls the scientist.

Schauer and his colleagues secured the patients' feet to the pedals using special shoes, and attached electrodes to their legs at the knee flexor, knee extensor and hip extensor muscles. Then they fed data on the position of the pedals into their computer program. It was months before the software was running smoothly enough for all components to work seamlessly together. Finally, it happened.

A PERFECT BIOLOGICAL STIMULATION SYSTEM

From a laptop on the carrier rack, the software controlled the electric pulses issued by the small on-board battery and the electrostimulator. Whenever a pedal moved over the highest point on the curve, the electrodes at the knee extensor were activated and the muscle contracted. As soon as the leg was fully stretched, the knee flexor was stimulated and drew the pedal up again. Ultimately, the leg completed a perfect rotational movement. Without any engines to help them, the paraplegic patients were pedaling around on the special tricycle. "It gave people a wonderful sense of freedom to cycle about under their own power," says Schauer.

Of course, electrical stimulation is a long way from holding its own against natural nerve stimulation. Nerve pathways shoot their microimpulses into individual bundles of muscle fibers with high precision, while the electrodes fixed to the skin are the size of post-its and cause several muscles to twitch at once. Nor are they as accurate as nerve cords at dosing their energy. Consequently, the same muscle fibers are stimulated again and again, and the muscle fatigues quickly.

Schauer wants to improve this situation. In recent years, he has gradually come closer to the perfect biological stimulation system. First, he and his colleagues developed a kind of training ergometer together with medical device manufacturer Hasomed; it has been on the market for about five years now. Paraplegics and stroke patients with paralyzed legs step on the pedals as they sit in a wheelchair. The device includes an electric motor that helps the patients as they push the pedals.

Graphic: designergold, based on original material from the MPI for Dynamics of Complex Technical Systems

In an ongoing project, Schauer is bringing electrical stimulation a step further. This project involves not only the medical device manufacturer, but also neurologists from Berlin's university hospital Charité. Together, they are working on the details of a kind of intelligent ergometer. The pedals of this device hold force sensors that detect how strongly the leg is pushing, and this enables the software to adapt the strength of the current and intensity of the pulses to the muscle status.

The conventional ergometer had no such control loop; it simply sent pulses to the leg flexors and extensors as a function of the pedals' position. This meant that the muscle stimulation was always steady – but a muscle doesn't work like an electric motor. "Muscle effort varies depending on the patient's condition or even the time of day," explains Schauer. And then, of course, muscles become fatigued during exercise. The control loop receives data from the force sensors in the pedals, enabling the electrical stimulation to be adjusted so that now, if the muscle becomes fatigued, the device gives a stronger stimulus.

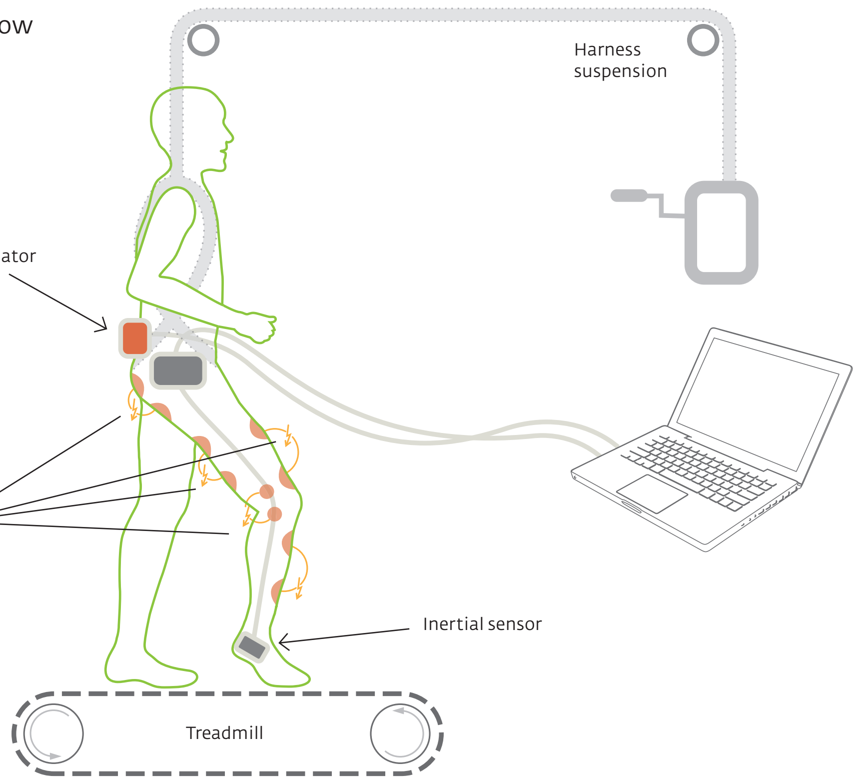
The new ergometer also features electrodes that not only stimulate the muscles, but actually measure their electrical excitation. These are known as electromyographs (EMG), a kind of ECG for muscle function. The EMG gives the control loop additional information about muscle status. This is particularly useful for stroke patients who need to train their legs. Electrical stimulation can support them in this, but using EMG, the system can detect exactly how fit the muscle is, how well it responds to stimulation and how much it contributes to the pedaling movement. A force sensor cannot provide such nuanced information.

And there's yet another new element. The only adjustments previously possible in electrical stimulation were the strength of the current and the duration of the pulse. This is not enough to simulate natural neuronal excitation, however, because how a muscle works also depends on the rate and frequency of the fine electric impulses. This was too much for the early control devices – Schauer and his colleagues had to resort to screwing and soldering to build the first muscle pulse generator.

WORKOUT FOR THE CARDIOVASCULAR SYSTEM

Consequently, they built this technology into the new ergometer, resulting in vastly improved workouts for paraplegic patients. Above all, the legs take longer to fatigue. And then there's the auxiliary motor that supports beginners as they pedal. For others, the ergometer workout is part of their daily fitness program, and the stronger their muscles become, the less the motor helps them. "Paraplegics have only a limited range of movement, so working with the ergometer is especially important for their cardiovascular system and general condition," says Schauer. >

Photo: Sven Döring



above | Learning to walk again after a stroke: The brain can compensate for damage in the areas that control the motor function of the legs if passive walking is used. Patients are held by a kind of harness while their legs are stimulated to walk on a treadmill. The ingenious control system enables fluid movements.

right | Walking without stumbling: The sensor on Thomas Brunsch's shoe measures the position of the foot. The electrodes on the lower leg lift the foot so that a stroke patient won't stumble while walking. The control unit in the belt bag calculates how strong the electrical signal must be to ensure that the muscles don't fatigue too quickly. Arm movements can be supported in the same way.

Electrical stimulation is even more significant for stroke patients as they seek to regain lost skills and overcome paralysis. In a stroke, clots block arteries in the brain, or in other cases, a cerebral artery bursts. Either way, the blood supply is cut off, and without fresh blood and its constant supply of oxygen, definitive tissue death occurs within a short time, resulting in paralysis. "Time is brain," as medical experts say.

Depending on which area of the brain is affected, various bodily functions previously controlled by that area will fail. A stroke often causes paralysis of the leg, but the brain can compensate for the damage. Healthy areas take over the functions of the damaged part, but only if the brain is taught the movement by repeating it many thousands of times.

Physiotherapists usually do this work – a back-breaking job. Patients are supported by a kind of mountaineering harness suspended from the ceiling as they walk slowly on a treadmill. In time with the steps, the therapist lifts the paralyzed leg and sets the foot back on the treadmill. Weeks of daily training are required before the patient learns how to walk again – and trusts that the paralyzed leg can bear their weight once more.

STROKE PATIENTS WALK WITHOUT STUMBLING

Once more, Raisch and Schauer's control systems have something to offer: As with the ergometer, they lift the knee, tilt the foot, and put it down again. Thanks to appropriate electrical stimulation, the muscles themselves do what therapists have usually done to date. It doesn't sound much more difficult than stimulated cycling, but a step is a fast thing. Depending on the pace, it might take only a second. The control system has to keep up and even work faster, because the muscle reacts to each pulse with a time delay. As a result, Schauer's path to achieving fluid movement was a long one. He and his colleagues spent several years programming and optimizing. A prototype of the control software is now being used in treadmill training at a clinical center.

With experience, Schauer's expectations of his electrical stimulation programs grew: first, the experiments with the tricycle and the ergometer, which guide and hold the patient securely as the pedals are turned; then walking on the treadmill while suspended; and finally, even more complexity – independent walking without stumbling. About one in five stroke patients who learn to walk again end up with "foot drop," a disorder in which the brain does not fully activate the dorsal flexor of the foot, that is, the muscle that lifts the toes when the foot swings forward. Initially, the dangling toes make patients stumble, but in time, they learn to use an evasive movement, swinging the foot out to the side in a semicircle. This unsteady gait prevents stumbling, but is rather tiring. Climbing stairs becomes an arduous challenge.

Graphic: designergold, based on original material from the MPI for Dynamics of Complex Technical Systems

Photo: Sven Döring

For a number of years now, electrostimulatory walking aids have been used for foot drop. Patients wear shoes with pressure sensors. When they lift a foot off the ground, the sensor in the sole of the shoe sends a command to the stimulator, which emits such a strong current that the foot is lifted way up high – a safety measure to ensure that nobody stumbles. Unfortunately, this causes rapid fatiguing of the muscle. These conventional systems offer only simple on-off functionality; they have no way of adapting to the muscle condition or effort of the patient's leg. Once again, the control loop provides a solution.

How, then, to fix foot drop with correct positioning and without over fatiguing the muscle? In order to walk safely, the foot must land, roll and lift perfectly, with a precision of fractions of a second. One of Raisch's doctoral students at the Magdeburg-based institute had an inspired idea: it should be possible to control such a system accurately if the exact position of the foot is known – preferably using a sensor on the shoe itself. He worked meticulously on this idea for the full course of his doctoral studies, and finally came up with a small sensor that could be clipped onto a shoe. This fast-acting gadget takes mere milliseconds to calculate the height, acceleration, position and angle of the foot.

Speedy calculation of the position is not enough, however, because the muscles need to be stimulated just as quickly. A zippy control system was also required. "It quickly became clear that the whole system is too slow if we want to calculate the position while the foot swings forward and adjust the intensity of the stimulation at the same time," says Schauer. A muscle is simply too sluggish. Before it reacts to an electric pulse, the foot is already back on the ground.

Instead, the software analyzes the data after each individual step in a matter of milliseconds, and has a suitable stimulation pattern ready before the next step is taken. This means that the system constantly learns from past steps and adapts the pulses for each subsequent step. "Iterative learning" is Raisch's term for this strategy, which makes flexible correction of foot drop possible for the first time.

First, though, the team of scientists had yet another hurdle to overcome. Every sensor, every technical system, makes tiny mistakes and therefore, in the course of time, deviates from the ideal or target value. A wristwatch, for instance, may be several minutes slow after some weeks. If these errors accumulate, the situation becomes critical. It's no big deal with a wristwatch – we just reset it; but a position sensor that deviates significantly from the correct position after 50 steps is dangerous, as it will cause patients to stumble. Consequently, the electrical engineers designed the software in such a way that it constantly self-calibrates and errors do not accumulate.

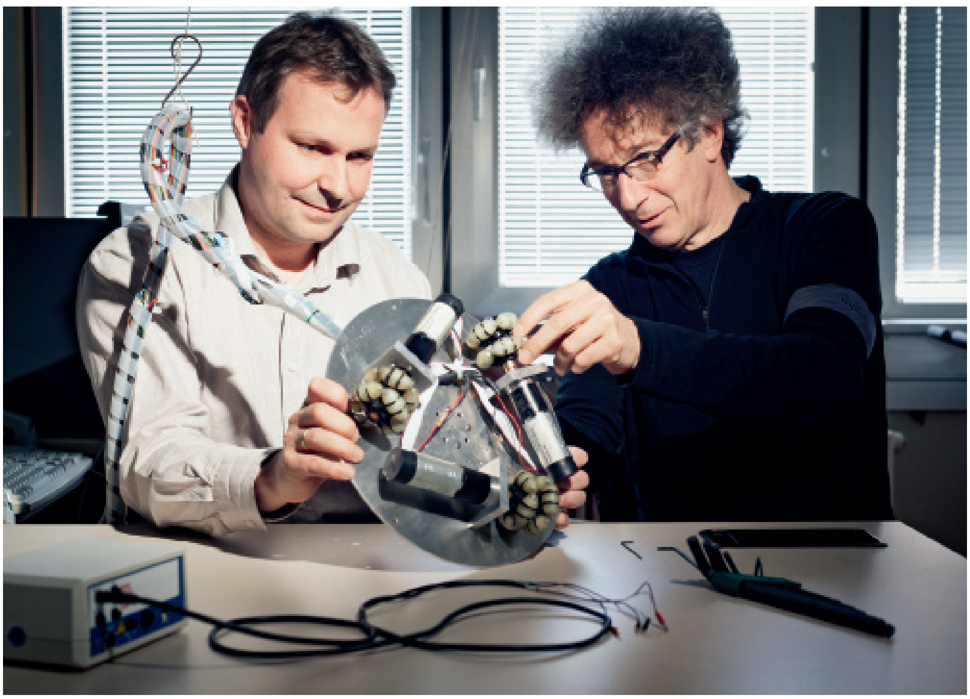
For now, the sensor is too expensive for general use in the daily lives of stroke patients, and too big – although it is only the size of a matchbox. Besides, the sensor, stimulator and controls interact only by means of a complex wiring system, which can be rather troublesome in daily life. A wireless solution would be better.

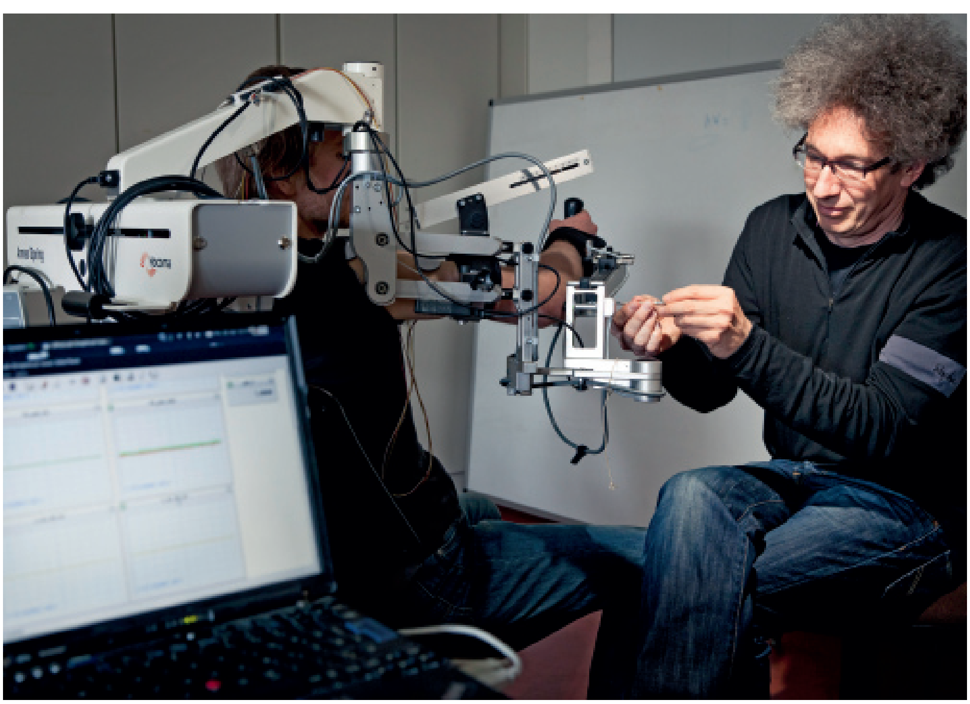
As a result, Schauer and his team have been working for some time on another, rather unusual position sensor: a bioimpedance sensor. This measures the electrical resistance between several points on the lower leg. What is really fascinating is that, as the leg moves, and particularly as the skin and muscles stretch, the electrical resistance (or bioimpedance) changes. Ultimately, this means that a control system could deduce the position of the foot and activate the dorsal flexor with a perfect fit.

THE GOAL: SOCKS WITH INTEGRATED ELECTRONICS

Schauer's bioimpedance work is still in its infancy, but the procedure seems promising, given that it is a low-fuss system. However, it can't quite yet manage without wires because the electrodes on the lower leg need to be connected to the control electronics. Still, Schauer has thought up a solution for this, too: one day, patients will wear stockings with integrated electrodes and contacts. Unfortunately, the sensor electronics currently used to determine the position of the foot could hardly be knit into a sock.

Schauer's newest project, which he is working on with doctors from Berlin's trauma center (Unfallkrankenhaus Berlin – UKB), is also based on bioimpedance measurements and focuses on the treatment of swallowing disorders. Just as the death of brain tissue following a stroke often causes paralysis of the leg muscles, it can also affect the muscles that control swallowing. In such cases, the windpipe is no longer fully closed during the swallow re-





Hand in hand with robots: Thomas Schauer and Jörg Raisch assemble a robot with wheels and motors visible underneath (top). Stroke patients can hold a handle on the other side. Working with electrical stimulation, the robot guides their hand over a table so that the brain can re-learn how to control the arm. The exoskeleton (below) can also be used in rehabilitation, supporting stimulated arm movements in all directions. Using this commercial system, the Max Planck scientists are also developing controls for a mobile prosthesis for patients with progressive muscular paralysis.

Photos: Sven Döring

Resistance when swallowing: While Corinna Schultheiss swallows, Holger Nahrstaedt uses sensors to measure bioimpedance at her neck. The results will help the researchers develop an implant to stimulate laryngeal movement.

sponse. Food and drink slip into the lungs, leading to severe inflammation. Often the only solution is a tracheotomy or tube feeding, where the care assistant injects the food into the stomach through a tube.

MEDICAL INNOVATION AWARD FOR SWALLOWING AID

If it were possible to control the larynx area in the same way as a paralyzed leg, it would mean that the swallowing muscles could be suitably activated and the windpipe protected. The system would monitor the muscles using bioimpedance measurements and assess whether food is moving toward the esophagus or accidentally ending up in the windpipe.

The concept of detecting choking by means of external measurements seemed rather absurd initially, even to Schauer and his medical colleague, Rainer Seidl of UKB. So they brought a cow's throat into the laboratory and inserted wafer-thin needle electrodes into the tissue. "We really had no idea whether or to what extent changes in resistance could be measured from the outside when fluids flowed through the larynx."

The first attempts were promising, so Schauer and his colleagues ultimately attached electrodes to their own necks. "Now we really can use the resistance values to draw conclusions about muscle activity and the swallowing process." A short time ago, Germany's Federal Ministry of Research awarded Schauer and Seidl the Prize for Innovation in Medical Technology. This financial injection is helping them drive the project forward. Their goal is to create a high-tech implant that few people have ever heard of. Prosthetic arms and legs are nothing new, but if all goes well, Raisch, Schauer and Seidl will achieve something quite different: an electronic swallowing prosthesis to get the larynx moving. ◂

GLOSSARY

Functional electrical stimulation
This method is used when the areas of the brain responsible for muscle control are damaged and can't emit signals along the nerves. External currents are used to stimulate the nerves and make the muscles contract.

Electromyography
provides information on the electrical activity of a muscle. It measures both the spontaneous activity of the muscle at rest and the action potentials of the contracted muscle.

Bioimpedance
A measure of the body's resistance when an external current is applied.

Photo: Sven Döring