The Economist

Rewiring nerves

How to rewire the nervous system

Biomedicine: Doctors are rerouting nerves to give patients more natural control of prosthetic arms and bring paralysed limbs back to life

Sep 2nd 2010

Natural control of an artificial arm

IT IS known as “phantom limb syndrome” or “phantom pain”. But this strange phenomenon feels all too real to the people it affects, and can be agonisingly painful. Amputees and people who have become paralysed may still “feel” a missing limb or a part of their body, even though it is no longer connected to their nervous system. Yet such sensations offer confirmation that even when a limb has been severed or cut off from the nervous system, the nerves that once serviced it remain alive and well. Doctors are now finding ways to put these nerves to good use, by rewiring them to control prosthetic limbs or reanimate paralysed limbs.

Moreover, rewiring the nervous system should allow amputees to gain a sense of “embodiment” of a prosthetic. That is, by controlling and sensing the prosthetic using the same neural pathways and parts of the brain that once governed the real limb, the prosthetic can be made to feel and act like a genuine extension of the user’s body. And by stimulating the nerves in the legs or arms of paralysed patients—nerves that have been cut off from the central nervous system—it is possible to create co-ordinated movement of great subtlety. For example, the hands of paralysed patients have been stimulated to enable them to grasp and turn door knobs. And with careful control and co-ordination of the muscle groups in their legs, patients can even rise from their wheelchairs and take steps.

Prosthetic limbs are becoming increasingly sophisticated, but it can be very difficult to control them in a natural way, says Paul Marasco, a biomedical engineer at the Louis Stokes Cleveland Department of Veteran Affairs Medical Center, in Ohio. For example, patients control some motorised devices by flexing muscles in their remaining stump, shoulder or chest. These muscle movements are detected by electromyography (EMG) sensors on the skin, and the signals are translated into movements by the prosthetic.

This approach can provide incredible control over an artificial arm, but patients often prefer to use simpler, mechanical prosthetics. For one thing, such devices allow the patient to sense the movement of the arm through a system of cables which are used to control the device, usually by attaching them to the opposite shoulder. So even when their eyes are closed they can get a sense of whether an artificial arm is extended, or if there is resistance to a grasping motion, making the limb feel less detached and unnatural than an EMG device. Another problem with EMG prosthetics is that patients literally have to retrain their brains to make new associations between muscle movements and their outcomes—a shoulder flex could become a grasp motion, for example, while a twitch of pectoral muscle in the chest may extend the artificial arm.

But there is a way to overcome both these difficulties with motorised limbs, using a technique called “targeted reinnervation”. Pioneered by Todd Kuiken, director of the Neural Engineering Centre for Artificial Limbs at the Rehabilitation Institute of Chicago, along with his colleagues Aimee Schultz, Blair Lock and Dr Marasco (who was formerly at NECAL), this involves rerouting the nerves that would have originally controlled and sensed the missing limb and connecting them instead to other parts of the body. By rewiring a missing arm's motor nerves to muscles in the remaining stump, shoulder or chest, for example, and rewiring the arm's sensory nerves to the skin in these regions, a channel is opened to the part of the brain that once controlled the missing limb.

It is a strange and slightly ghoulish idea, because it means that if a patient tries to flex his missing finger, for example, a muscle in another part of his body (which is now connected to the nerves that used to control the finger) contracts instead. "When the amputee wants to open or close their hand, these muscles twitch," says Dr Marasco. EMG sensors detect these signals and translate them into control signals that cause the mechanical hand to open and close. The patient can then open and close his prosthetic hand simply by trying to move the fingers that are no longer there.

The sensory side of things works in a similar fashion, but instead of reconnecting nerves to different muscles, they are instead rewired to the skin's underlying sensory systems. "They hook themselves up to the receptors in the skin," says Dr Marasco. So when the reinnervated skin (on the chest or shoulder, perhaps) is touched, it registers to the patient as a sensation in the missing limb. "They have very distinct sensations that they can feel: vibrations, temperature and pressure," he says. This means sensors in a prosthetic limb could, in theory, stimulate the reinnervated skin to cause realistic sensations.

The first example of sensory reinnervation actually happened by accident back in 2003, when the surgery was first performed, says Ms Schultz. Several patients underwent surgery to reroute their motor nerves to different muscles, but in the process the sensory nerves reinnervated themselves too, attaching themselves to the skin receptors. This was discovered when one of the patients was having alcohol dabbed on his chest, and remarked that he could feel it in his missing limb. "Everyone was stunned," says Ms Schultz.

This opened the door to the possibility of providing feedback to patients. But enabling patients to sense things will mean developing sensors to go on prosthetic limbs, and corresponding devices to stimulate the reinnervated skin. To this end Dr Marasco and his colleagues have been working with Ed Colgate, a haptics expert at Northwestern University in Evanston, Illinois, and Kinea Design, a biomechatronics firm that is also based in Evanston, to develop tactile devices that would attach to the amputee's skin.

> "Targeted reinnervation involves rerouting nerves that originally controlled the missing limb."

Multisensory devices have already been developed and tested on reinnervated amputees, relaying sensations of contact, pressure, vibration, shear force and temperature. These prototypes use mechanical stimulation to create these sensations, and electrical Peltier devices to generate different temperatures. Patients feel the sensations in their missing limbs, and one patient was even able to discriminate by touch between sandpaper, Teflon and the bumpy texture of a computer ribbon cable using artificial touch sensors.

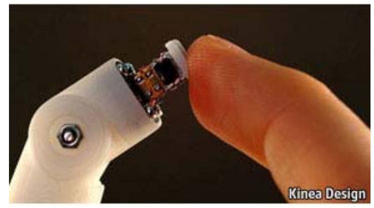
Although there are far fewer sensory receptors in the skin of the chest, shoulder and upper arm than there are in the hand, the tactile acuity of these regions' skin appears to increase when reinnervated, says Dr Marasco. It's not entirely clear why, but it probably comes down to how the brain perceives these signals. "It appears that there is much more processing power devoted to these nerves," he says. Just how much tactile acuity can be achieved remains to be seen. "This is unchartered territory," says Dr Marasco.

When it comes to rewiring the limbs of paralysed patients in order to reanimate them, however, a very different approach is required. Researchers must instead target the deeper nerves that control movement. The idea of electrically stimulating the muscles of paralysed people is not new. Many different techniques have emerged over the years, most of which involve applying small jolts of electricity externally to muscles, via electrodes on the skin, to make them contract. Besides offering a means of exercising the muscles, and so preventing atrophy, the hope is that this "functional electrical stimulation" might also help restore mobility to patients.

Reanimate this

But external stimulation is less than ideal, says Dustin Tyler, a biomedical engineer at Case Western Reserve University in Cleveland, Ohio. The muscles in the legs are so large that the whole muscle does not contract, he says. So he and his colleagues have been looking at ways to activate these muscles by tapping into the femoral nerve, in the groin. "By moving back to the nerve you get the whole muscle," he says. The femoral nerve is divided into several dozen separate bundles of nerves, called fascicles, each of which contains hundreds if not thousands of individual nerves. Different fascicles lead to different muscles, so stimulating groups of fascicles at different times and by different degrees should enable co-ordinated leg movements.

Stimulating fascicles can be done by wrapping so-called cuff electrodes around them. The problem is that within the femoral nerve all the fascicles are themselves bundled together, making it difficult to stimulate them individually. But Dr Tyler has developed a cuff electrode that allows discrimination by gently flattening the femoral nerve without damaging it. Most electrodes are designed around the assumption that nerves are round, he says. But flattening them out makes the individual fascicles accessible, like the parallel wires in old computer cables, says Dr Tyler.



Getting touchy-feely with haptic sensors

And by controlling the intensity and duration of the electrical pulses applied, it is possible to specify just how much of the tissue is contracted. Besides getting patients to stand and take steps, albeit tremulous ones, Dr Tyler and his team have used an early version of this technique in a patient’s arms to enable grasping movements. They hope to carry out the first permanent implantation of their new electrodes in November.

But to create full mobility, what is not clear is how a patient might control such a system. Some sort of joystick interface could be used to allow paraplegic people, who still have control of their upper body, to activate certain patterns of co-ordinated movement, such as standing, walking and sitting. But in the long term the ultimate goal would be to place electrodes in the motor cortex of the brain.

That is some way off. But targeted reinnervation is now available as a treatment. More than 40 people around the world have undergone the procedure so far. Even though patients can currently use it only to control their artificial limbs, sensory feedback is coming. And these are merely the first examples of what can be done by rewiring the nervous system, and linking nerves to electronic and robotic devices.

Technology Quarterly