[Getty]

SMARTER PROSTHETICS

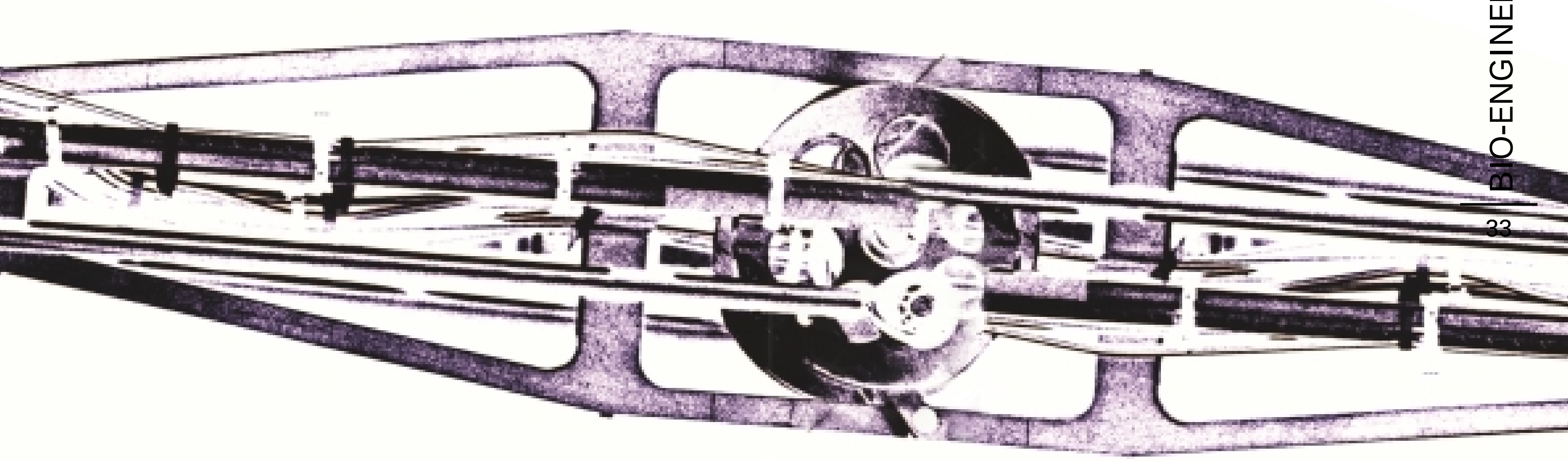
Researchers are working to develop artificial limbs with almost life-like levels of functionality and control

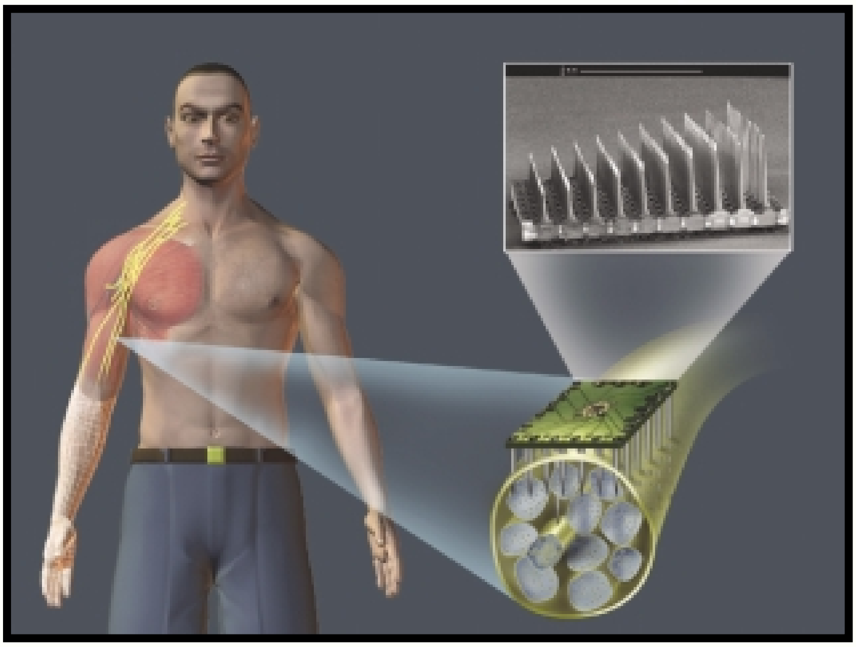
by Christine Evans-Pughe

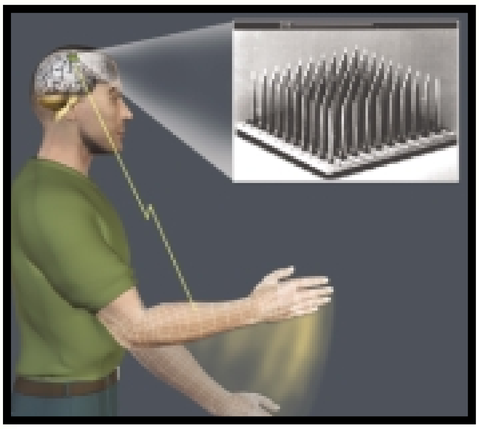
THE USE OF BODY armour by US troops in Iraq means that many soldiers are surviving injuries that would otherwise have killed them. The downside, according to a 2004 study in the *New England Journal of Medicine*, is that the percentage of casualties suffering limb amputation is twice as high as in previous wars. For obvious reasons, research activity into ways of building better prosthetic limbs has never been higher.

A $7.2m project awarded to the Providence VA Medical Center, Brown University and the Massachusetts Institute of Technology (MIT) by the US Department of Veterans Affairs (DoVA), aims to create 'biohybrid' limbs that integrate human tissue with a prosthesis controlled by the amputee's muscles and brain signals. In a parallel programme, the US Department of Defense's Advanced Research Project Agency (DARPA) has put $70m into prosthetic arm research. By 2009, DARPA plans to have a mechanical arm ready for clinical trials, controlled via the amputee's nervous system and with all the properties of a real limb.

These programmes sound rather ambitious, but they build on a great deal of established work in areas such as tissue engineering, machine learning, robotics and neuroprosthetic design. "If we now integrate these technologies, I think we will see a







major shift in this area of medicine," says Prof Hugh Herr, director of the biomechatronics group at MIT's Media Lab and head of the team that is developing the robotic leg for the five-year DoVA project.

Implants can be embedded in a peripheral nerve (above) or a cortical nerve (right)

THE MAGNETIC KNEE

Herr was principal investigator on the research team that created the Rheo knee, one of the most advanced commercial prosthetic knees on the market. A development between MIT and the Icelandic prosthetics firm Ossur, this is an aluminium prosthesis that automatically adapts to the individual's walking style by electronically sensing knee position and load so that it can deliver the right resistance during each step.

The adaptability is delivered by a microprocessor-controlled magnetorheological (MR) actuator at the knee joint that changes resistance in real time with the inputs of force and position sensors, sampled 1000 times per second.

The MR fluid has small iron particles suspended in oil that solidify into a paste in response to an applied magnetic field. As the knee rotates into flexion or extension, fine rotary blades shear the particle chains to create resistance. "It allows for very easy walking," explains Herr. "Using the MR fluid in the shear mode has the advantage that even at very high resistance or high damping, the fluid pressure remains low, unlike in a hydraulic cylinder where the greater the damping, the higher the fluid pressure, which can rupture the seals."

There are five sensors within 10cm of the MR joint. An angle sensor measures the knee flexion angle, and this signal is also is used to estimate the knee's angular velocity to determine whether it is flexing or extending. There are also four axial force sensors – two at the back of the knee and two at the front – which measure the force from the ground to determine whether the prosthetic foot is on or off the ground.

The DoVA wants a device that behaves like a natural leg and that can, ultimately, be bolted to an amputee's existing limb. "These new legs will more closely model the human musculoskeletal architecture and the way energy flows from tendon to tendon when a person walks," says Herr.

The experimental limb will have an MR knee joint and use similar sensors to those on the Rheo knee, but in greater quantity. It will also employ a more powerful microprocessor. Herr's team is currently building an independently powered foot/ankle system that can change stiffness and damping, and can thrust the user forward like the real →

> "MOTOR CONTROL SIGNALS SEEM TO BE VERY PLASTIC AND THE BRAIN CAN LEARN TO USE DIFFERENT NEURAL PATHWAYS TO ELICIT MOTOR FUNCTION" – *STUART HARSHBARGER, APL*

thing. Herr is unwilling to discuss details of the actuation systems, but says the team is looking at some novel tendon-like spring materials powered by electric motors. The design may also feature electro-active polymers that change shape when a voltage is applied.

Eventually, the MIT researchers hope to be able to control the prosthetic limb via a tiny injectable sensor called the BION, (developed by a US medical research firm called the Alfred Mann Foundation) that will pick up electrical signals from the muscles inside the leg and wirelessly send movement instructions to the limb.

MIND CONTROL

A group at Brown University is investigating whether the Braingate brain implant, from the US company Cyberkinetics, has the potential to usefully turn brain signals taken directly from the motor cortex into prosthetic limb movements. This 100-electrode device, based on a microelectrode array from Utah University, is already undergoing clinical trials. Last year, a quadriplegic BrainGate trial participant demonstrated direct control of various external devices including a computer cursor and a prosthetic hand, along with rudimentary control of a multi-joint robotic arm.

"Although these were very simple tasks, it highlighted the potential for intra-cortically recorded neuronal ensembles [populations of nervous system cells involved in a particular neural computation], to be harnessed by someone with paralysis or limb loss for control of an external device," says Leigh Hochberg, associate investigator in the centre of restorative and regenerative medicine at the Provenance VA Medical Centre and investigator in neuroscience at Brown University.

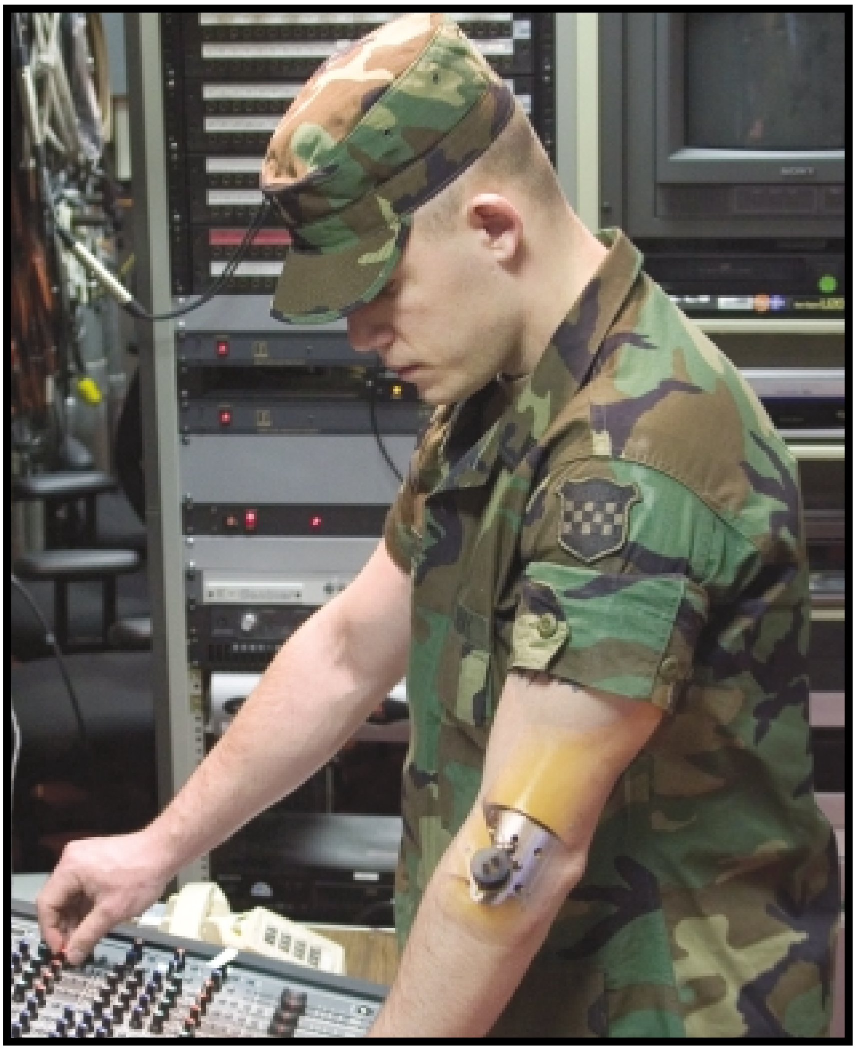
THE BEE'S KNEES

Above: The Power Knee

The latest innovation in commercial prostheses is Ossur's Power Knee, the first motorised leg prosthesis on the market. Developed by Ossur in partnership with the Canadian research firm Victhom, the Power Knee mimics lost muscle activity by powering ankle and leg amputees up stairs, or up from a sitting position.

Amputees take their first step with their sound leg, which has around 18 sensors positioned in a pad under the foot to measure motion, load and position of the limb at 1350 times per second. The information is transmitted via Bluetooth to a microprocessor in the Power Knee, which, having detected the type of activity the user is engaged in, calculates the precise amount of power needed to generate the matching prosthetic function. A permanent magnet electrical motor drives the knee joint. Compared to a non-motorised prosthesis like the Rheo Knee, "the Power Knee is like riding a motorbike rather than a bicycle, " comments Kim De Roy, Ossur's product manager for R&D.

Victhom is now working on a way to try use the peripheral nervous system to complement the network of sensors and to aid the analysis of movement. Clinical trials using an embedded electrode in the limb could start this year, says Stephane Bedard, Victhom's founder. "We have the technology to sense the neuronal activity of any type of peripheral nerve, so it is possible to extract the sensory signals and the motor signals from those nerves, interpret it and then send it wirelessly to the microprocessor to dramatically enhance the capability of the controller to interpret what the amputee wants to do."



Above: **APL arm – how it might look**

Hochberg, who is involved in the BrainGate trials in his role as a neurologist at Massachusetts General hospital, is encouraged by the results, but says that further development is needed to decode the array's output signals and convert them into useful information. "Amongst the challenges is being able to distinguish from the multitude of signals that are available from any small ensemble of neurons and to use that signal usefully," he says. Also there is a need to make the BrainGate device fully implantable rather than being a wired device as it is today.

GETTING REAL

Building a mechanical arm that acts like a real one is probably the biggest challenge in prosthetics. Currently, the best prosthetic arms are operated by muscle constrictions, and are limited to three degrees of freedom. "You can have a fully powered elbow, a wrist rotator, and the hand opening and closing at different speeds. There are also devices that sense when a grasped object is starting to slip, and tighten the hand," explains Laith Al-kazaz, R&D Manager of the UK prosthetics firm RSL Steeper Ltd.

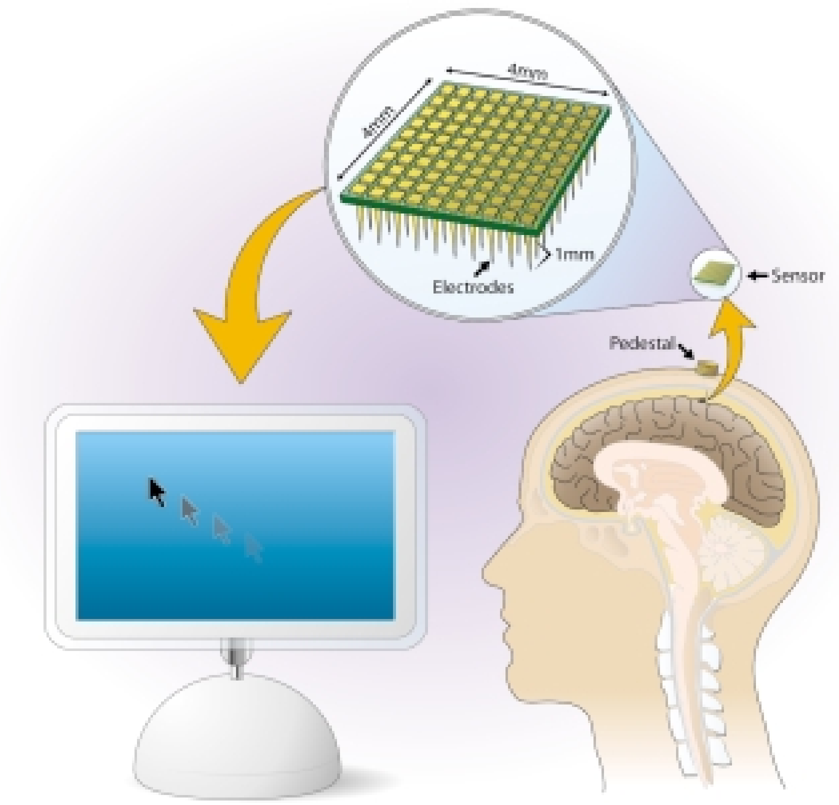
The bulk of DARPA's $70m is going into a programme with the gung ho name of 'Revolutionising Prosthetics 2009' which aims to reproduce all 22 degrees of freedom of a real arm with natural movement control and sensory feedback for touch, temperature and location provided via brain or peripheral nerve implants. One of DARPA's specifications is that the user should be able to differentiate between 2mm of movement and 0.1 Newton in force and sensation.

Around 30 organisations across the US, Canada and Europe are involved in this effort. The Johns Hopkins University Applied Physics Laboratory (APL) in Maryland is coordinating the whole thing under the leadership of Stuart Harshbarger, a senior scientist at APL with experience in electronics system integration and communications engineering.

APL is developing a virtual environment to help explore all the function and control concepts as the project progresses. It is also making a prototype arm using traditional electromechanical methods such as DC motors, brushless motors and differential drives. Other partners are developing more advanced actuation systems such as gas actuation (also known as air muscles) and miniature hydraulics.

The proposed neural implant is a wireless version of the University of Utah's microelectrode array. The Utah group has already made a prototype that integrates a chip to amplify, condition and digitise the neural signals from each of the 100 electrodes. The signals are transmitted using a fully integrated 433MHz transmitter, with power delivered inductively via a coil that doubles up as an antenna. At a supply current of 1.9mA, the Utah researchers have shown that they can receive data at a range of 13cm.

Achieving sensory feedback is one of the most interesting problems. If you embed



Above: **The Braingate implant aims to link brain and computer**

an implant into a peripheral nerve, the electrodes will give you access to a mix of motor control and sensory feedback fibres, however you won't know how the sensory receptors map back to the brain. "Motor control signals seem to be very plastic and the brain can learn to use different neural pathways to elicit motor function, " explains Harshbarger. "The sensory receptors seem to be more fixed, so with a receptor that corresponds to temperature it will be difficult to re-map it into something that gives you pressure." However he thinks that by using the virtual reality environment and some interaction with patients, it should be possible to find out which pathways an electrode has tapped into.

Separate arrays may be required for recording the motor-control signals and for stimulating the sensory feedback pathways. "If you have two devices separated by distance and positioned so one is upstream from the other, then there shouldn't be an issue with crosstalk. If there is, we can separate the signals out because we know the latency between the two of them," says Harshbarger.

Safe operation, of course, has to be a paramount consideration in the design of a control system for a large mechanical object with so much freedom of movement. "The interpretation of the inherent signals in the body isn't going to be perfect, so there will be times when we get the specific intent wrong or there is some environmental interference that changes what the overall signal pattern looks like," he explains. "We have to be prepared for those inadvertent motions, so if the control system says move the limb at a certain rate towards something sensitive like the patient's face, there is some override."

It is a daunting project, with a degree of political motivation behind the funding, but if it meets its goals – and Harshbarger is confident of success – it will, DARPA believes, "leapfrog the industry forward 50 years. " ■

MIND CONTROL

The idea of using the body's natural motor signals to operate an artificial limb is not new. Myoelectric prostheses, operated by the electrical signals generated by contracting two sets of muscles on the residual limb, have been available to upper-extremity amputees for 30 years. Electrodes placed on the surface of the skin detect and amplify the muscle signals (these range from 3µV to 300µV), which then travel by wires to circuitry that opens and closes an electrically powered mechanical hand, for instance. Typically, it is only possible to operate one movement at a time.

In the last few years Todd Kuiken of the Rehabilitation Institute in Chicago has pioneered the technique of targeted reinnervation – grafting nerves from the amputee's damaged limb onto healthy muscle. The process produces additional control signals, allowing for simultaneous operation of multiple functions in an artificial limb. One patient had his shoulder nerves grafted onto his chest. When he thinks about closing the hand, the nerves cause small contractions in his pectoral muscles and the impulses are picked up via surface electrodes and carried to his mechanical arm.

Implanting electrodes (known as neuroprostheses) directly into the brain or in the peripheral nerves near the limb loss is the next logical step.