With better, stronger and faster components, the bionic age has finally arrived, says **Julian Smith**

FIVE years after he lost a leg to a landmine in Afghanistan, American war veteran Mike McNaughton can run well enough to coach his 11-year-old son's soccer team. This amazing comeback comes partly from his determination to get back on two feet, but also from a piece of high-tech hardware: a computerised, hydraulic knee that monitors and adjusts every step, with a response time in milliseconds. "Now I can run with the kids full blast and kick the ball around with them," he says.

After decades of amputees having to make do with designs that had changed little since the second world war, artificial limbs that predict their user's every movement and look like the real thing are finally breaking out of the lab. Yet convincing and comfortable synthetic limbs like McNaughton's are only the beginning of the bionic age.

Emerging prosthetic technologies promise not only greater power and flexibility but also pressure-sensitive artificial skin, and even limbs that are bonded to the body and controlled by the mind – and much of this within five years. Rebuilding amputees to be faster and stronger than before is rapidly becoming a realistic possibility. With

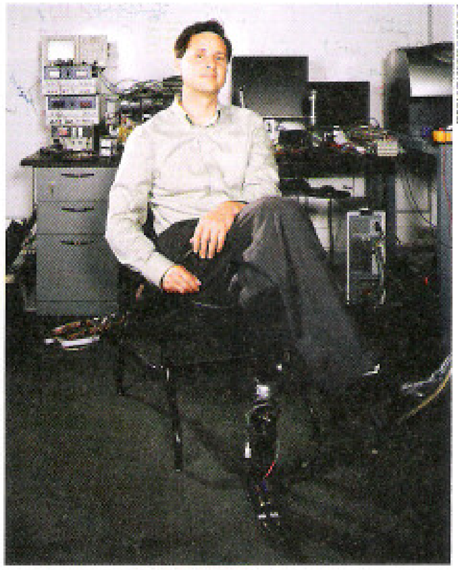
We have the technology

experimental prosthetics increasingly able to integrate with flesh, bone and the nervous system, the very idea of "losing a limb" may one day become obsolete.

"This is perhaps the most exciting time ever to be involved in advanced prosthetics," says John Bigelow of the applied physics laboratory at Johns Hopkins University in Baltimore, Maryland, who works on brain-controlled robotic arms.

There are many reasons for this bionic gold rush, says Bigelow. Smaller, better components have made it possible to pack more hardware into a limb than ever before. There are also more and more amputees in the US because of soaring rates of diabetes – which can cause nerve and vascular damage – and injuries suffered by soldiers in the Middle East. These factors have encouraged more investment in bionic technologies than ever before.

Double arm amputee Christian Kandlbauer shows how realistic prostheses can be



Bionics researcher and double amputee Hugh Herr, of the MIT Media Lab, aims to merge body and machine

The early results of this boom are now reaching the open market. For up to $30,000, a person who has lost a leg to illness or injury can obtain a prosthetic like McNaughton's, complete with "intelligent" software that learns a user's gait and can adapt to changing terrain. Examples include the C-Leg from German orthopaedic company Otto Block and the Rheo Knee, which McNaughton uses, from the Icelandic company Össur. These use a combination of hydraulics and motors to make carrying the leg less tiring, plus carbon fibre to mimic the elastic properties of bones and tendons.

Prosthetic feet have always been particularly tricky to design. The muscles in natural feet and ankles constantly add or damp forces as necessary, and the elasticity of our tendons lets us walk using relatively little energy. Lower-limb amputees, though, "walk slower, use more metabolic energy and are less stable – even on flat ground", says Hugh Herr, director of the Biomechatronics Group at the Massachusetts Institute of Technology and himself a double lower-limb amputee. To tackle this problem Herr's group has designed a prosthetic foot, the iWalk PowerFoot One, which uses an electric motor and tendon-like springs to propel the user forward or slow them down, controlled by two microprocessors and six sensors that measure the ankle's position and the forces it is experiencing.

Bionic arms

Upper-limb prosthetics, however, have lagged behind. This is in part because arm and hand amputations are less common than those of lower limbs, and also because arms are smaller and have a greater range of movement than legs, making it more difficult to pack in the hardware needed to mimic a real arm. This too is changing, as ever smaller components become available.

Perhaps the smallest and most powerful yet is the i-Limb from British company Touch Bionics in Livingston, West Lothian. It's a lightweight plastic hand in which each digit contains its own motor and can move independently in response to signals from two sensors attached to skin elsewhere on the user's body. These sensors pick up "myoelectric" signals – the electrical impulses that cause muscles to contract. Users move the hand by tensing certain muscles in a particular way to initiate pre-programmed grip patterns. For example, one pattern lets users hold a key between the thumb and the index finger, and another makes the hand point with the index finger. The hand also boasts a "stall detector" system that stops the hand contracting further once it has sufficient grip on an object.

According to user John German, who lost his left hand to a congenital nerve condition, people frequently mistake his i-Limb, covered with a realistic silicon "skin", for a real hand. Even so, some users – particularly in the military – prefer the "Terminator look" of the naked device, so the company now also offers clear coverings.

Entire bionic arms are also in development. The Luke Arm has been developed by the creator of the Segway transporter, Dean Kamen, at the medical technology company Deka based in Manchester, New Hampshire. It was financed by the US Defense Advanced Research Projects Agency (DARPA): troubled by the growing ranks of war veterans returning from Iraq and Afghanistan having lost limbs to bombs, DARPA has pledged almost $50 million in research funds towards the creation of a realistic, thought-controlled bionic arm.

The Luke Arm, inspired by Luke Skywalker's bionic hand in the *Star Wars* films, allows users to shake hands, turn a key in a lock and perform movements as delicate as picking up a coffee bean. It is controlled by myoelectric sensors or a customisable foot-controlled joystick worn inside a shoe. Tactile feedback comes from a small oscillating motor held against the user's skin, which vibrates at a higher frequency as grip strength increases.

Advanced as these devices are, there are still many hurdles to overcome to achieve ▶

Amputee triathlete Scott Rigsby has high-tech prosthetics for swimming, cycling and running

the perfect prosthetic: one that links directly to its user's bone and nervous system to become an integrated extension of the body that just happens to be metal and plastic.

Realistic, sensitive artificial skin would be an important step towards making the prosthetic feel like an extension of the body. The best available skin coverings, or "cosmeses", are already surprisingly lifelike, complete with simulated pores and hair, but don't provide any tactile feedback. Researchers at NASA, Oak Ridge National Laboratory and the National Institute of Aerospace (NIA) have created small patches of thin, flexible cosmeses with inbuilt touch sensitivity (see diagram, opposite).

Electric touch

The synthetic skin is made of a rubbery polymer composite that is strong, light and flexible. Embedded within it are single-wall carbon nanotubes that give it piezoresistive properties – that is, pressure on the material changes its electrical resistance. By measuring the changing resistance of the nanotube layer, the skin can detect different pressures and kinds of contact – a brush or a tap, for example. This is a long way from the subtle sensitivity of human skin, says NIA researcher Cheol Park, but "even this simple sensing capability, along with temperature sensing, would be a revolutionary sensation for many amputees". The team are now working on ways to relay these signals to users' nerves and brains. They are also trying to improve the material's minimum sensitivity threshold.

Another way to make an artificial limb feel more real is to attach it permanently, or at least semi-permanently, to the body. At present, even the best designs are worn rather than attached. This can cause a number of problems: sockets can become sweaty and chafe, and any looseness costs control and power. Instead of just pulling the straps tighter, some researchers wonder, why not connect an artificial limb directly to the skeleton? Using techniques originally developed for dental implants, a team of orthopaedists led by Rickard Brånemark at the Sahlgrenska Teaching University Hospital in Gothenburg, Sweden, is testing just such a system. The team implants titanium extensions into residual bones in the upper leg or upper arm, leaving a 2-centimetre-long strut protruding through the skin, to which the prosthetic limb attaches. This socket-free system means the artificial limb is easy to attach and remove and does not interfere with the movement of the main limb joint.

"Artificial limbs may soon give natural ones a run for their money"

The system is now undergoing trials, and users say that their mobility and comfort have improved, and they are able to use their prosthetics for longer periods. Infection of the skin around the strut is still a problem, though, and excessive forces could damage the already weakened residual bone.

A British team recently announced that it has found a way around the infection problem. By making part of their titanium bone implant porous, they have been able to encourage skin, muscle and bone to grow through and around the strut, effectively incorporating it into the body. This "seals the interface and prevents infection", says Gordon Blunn of University College London, who designed the implant.

The next step towards making an artificial limb a true extension of the body is to connect it directly to the nervous system. This would mean tapping brain signals, decoding them in real time and routing them to the prosthetic. Sensory input would also need to be relayed back from the prosthetic to the central nervous system.

Bigelow's group is trying to achieve some of this with a newly designed robotic arm, the Proto 2. The arm is light and strong, with "bones" made of carbon fibre and high-strength alloys, and has nearly as much dexterity as a normal arm: it contains 25 motors and microprocessors that can perform most of the movements a natural arm can, and almost as quickly. The team is also developing wireless devices the size of a grain of rice to implant in muscles near the prosthetic arm. When the muscles are contracted, these so-called injectible myoelectric sensors would transmit signals instructing the arm to move.

The team is also experimenting with more intuitive ways of controlling prosthetics, including a technique called targeted muscle reinnervation that has been developed by Todd Kuiken of the Rehabilitation Institute of Chicago. In this approach, residual nerves in the limb that has had a part amputated are transferred to chest muscles. These nerves once had the job of moving the arm, so when the brain tells the arm to move, the nerves will make the chest muscles contract in a specific manner. Since the chest muscles are relatively large, this contraction pattern creates a readable electrical signal that can be relayed to the prosthesis to tell it to move. Kuiken reported last year that a woman who underwent this surgery was able to use a prosthetic arm much like a real one. "I just think about moving my hand and elbow and they move," she said.

Ultimately, users want to sense and control artificial limbs via direct connection with brain activity. Experiments by Nitish Thakor's team at Johns Hopkins University have shown that this is, in theory, possible. In experiments, volunteers have operated a mechanical hand simply by concentrating while wearing a cap studded with electrodes

With looks like these, and thought control around the corner, will prostheses one day be augmentations?

that pick up some of the brain's electrical activity. The user's intentions, in the form of electroencephalograph (EEG) signals, are processed and used to control the hand. This non-invasive system is limited in terms of response time and the range of movement it can achieve, says Thakor, but it could one day be used in concert with more invasive systems, such as electrodes implanted directly into the brain.

In January 2008, Miguel Nicolelis and colleagues at Duke University in Durham, North Carolina, took a step in this direction by training a monkey to control a robot using only her brain. The team implanted electrodes into the primary motor and somatosensory cortices in the brain of a rhesus monkey named Idoya; these were the regions that showed activity when she moved her legs. Next they put Idoya on a treadmill at Duke while transmitting her brain signals over the internet to a robot in Kyoto, Japan, which she could see on a monitor. As Idoya walked, the robot walked, and when the treadmill was switched off she kept the robot walking for another 3 minutes using only her thoughts.

All in the mind

Nicolelis hopes this technology will help paralysed people walk, and his team is currently working on building a whole-body exoskeleton. The control technology could be applied to integrated prosthetics, he says: "One day we could create a bypass that allows the brain signals to be delivered directly to the limbs of the patient," whether those limbs are artificial, or natural but malfunctioning.

Other mind-control developments include early trials of a neural interface called BrainGate, designed by Cyberkinetics, based in Foxborough, Massachusetts. BrainGate has enabled a 24-year-old quadriplegic man to play video games, move a computer cursor and control a robotic arm through a computer chip implanted on the surface of his brain. Three US hospitals are recruiting patients for pilot clinical trials of the system. Next year Thakor's lab plans to hold the first human clinical trials of an implant specifically designed to control a prosthetic arm.

With brain control seemingly not far off, prosthetic limbs could eventually be as easy to control as they are strong and light. They would then be stronger and faster than the real thing. So what happens when they surpass the limbs we were born with, and a prosthetic becomes an augmentation?

This issue hit the headlines in the case of South African sprinter Oscar Pistorius, a double amputee who runs on curved carbon-fibre "blades" and narrowly missed qualifying for the Beijing Olympics. Sports officials had earlier argued that his prosthetic feet gave him an unfair biomechanical advantage – a conclusion that Herr and others refuted.

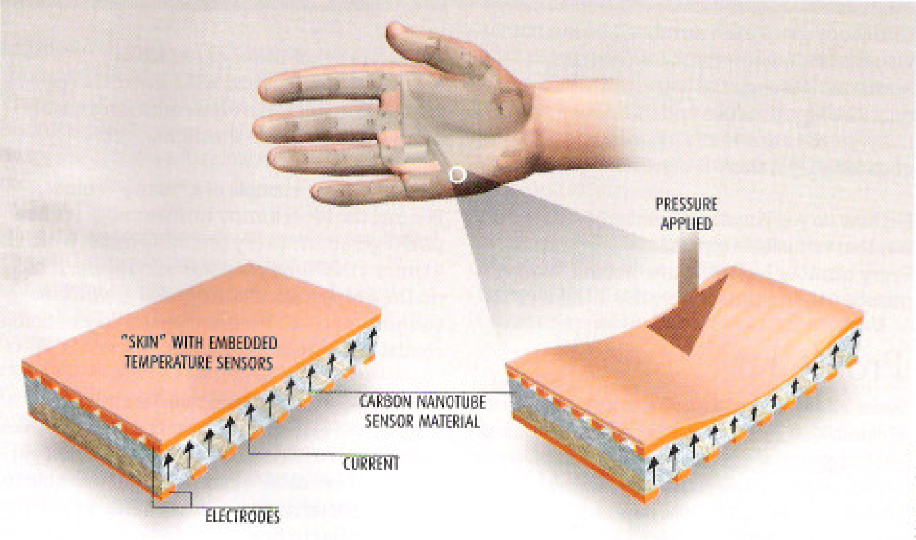
"It certainly will be possible in the future to build a limb that outperforms an intact limb," says Herr, "especially for running." Herr has special rock-climbing feet he designed himself for gripping tiny edges or wedging into cracks. He says he can scale harder routes now than he could before the accident that cost him his legs, although he is quick to acknowledge that he has also trained harder since then. David Gow, inventor of the i-Limb hand, agrees that artificial limbs may well give natural ones a run for their money, not just by being stronger and faster, but more aesthetically pleasing too.

Far-fetched as it may seem now, what if cosmetic surgery was to one day extend to replacing perfectly good arms and legs with more beautiful or powerful ones in the hope of producing another Michael Phelps or Victoria's Secret model? "Then we will have to evolve as a society a new morality, new ethics and codes of conduct, won't we?" says Gow. ●

Julian Smith is a freelance science writer based in Portland, Oregon

FEEL THE PRESSURE

NASA and the US National Institute of Aerospace are working on pressure and temperature-sensitive artificial skin



A current of less than 0.5 microamps is applied between arrays of sensors separated by a conductive layer of carbon nanotubes

When the skin is touched, the structure of the nanotube network changes, altering its conductivity. The electrode arrays register this change, and a microchip works out where and how hard the skin was touched

SOURCE: KANG, SAUTI, PARK (NIA)/HARRISON (NASA)