



HAS THE BIONIC MAN ARRIVED?

Is the ultimate union of man and machine finally upon us? **Julian Prokaza** considers the capabilities of artificial limbs and the potential for human endeavour

Steve Austin may have introduced the world to bionic technology, but in the 1970s, not even six million dollars could buy a man-made body part that worked as well as the real thing, let alone better. Forty years later, the situation has changed somewhat. Advances in electronics, mechanical engineering and medicine mean that bionic body parts are now in active use around the world. But allowing for the fact that they don't yet equip people with superhuman abilities, what do they provide that more traditional prostheses do not?

THE REAL DEAL

A prosthesis is an artificial body part designed to act as a cosmetic or functional replacement for the real thing, which might have been amputated or damaged as the result of trauma, disease or congenital disorder. Prostheses aren't new – there's evidence that artificial limbs were in use at least as far back as the first century BC. However, most of the improvements made in the intervening centuries have involved the materials used to make them.

Cosmetic 'passive' prostheses (such as a glass eye) serve little functional purpose, and they are usually an attempt to restore some semblance of normality. By comparison, 'functional' prostheses will go some way to actively replace a missing limb. However, it's difficult to duplicate the way a hand or joint works using mechanical components alone, and they can't offer the wearer any kind of fine control. A prosthetic leg may have a knee





◀▲ A cochlear implant transmits sound from a microphone to a receiver under the scalp, which then sends electrical impulses to the auditory nerve via the cochlea

joint that locks when the wearer puts weight on it, but this can happen only when the leg is fully extended and not, for example, when it's bent while climbing a flight of stairs.

Bionic prostheses offer a solution to such problems. Self-contained power sources perform a similar function to muscle, while sensors will detect what the wearer is doing and cause the limb to react accordingly. In addition to building artificial limbs that behave like the real thing, bionics can make possible completely new kinds of prostheses. Functional artificial eyes and ears simply wouldn't be possible by any other means. In other words, the technology is already at the stage where a bionic person is possible. In this feature, we'll take a look at what this entails.

NOW HEAR THIS

In the late 18th century, scientists discovered that electrically stimulating the middle ear resulted in the perception of sound. By the 1950s, they were measuring the effects of electrical contact with the inner ear's auditory nerve directly, and by the early 1960s, the basic principles of the cochlear implant were in place. Subsequent developments have focused on refining the way it works.

A cochlear implant restores hearing for people with severe or profound deafness caused by damage or impairment to the middle or inner ear. Since they just amplify sound, hearing aids are effective only for people with residual hearing. A cochlear implant bypasses the middle and inner completely, and connects directly to the auditory nerve responsible for sending sound information to the brain.

In theory, a cochlear implant works just like normal hearing: the ear drum transmits vibrations in the air to the fluid-filled cochlear behind it, which in turn cause the hair-like cilia inside to move and generate electrical impulses in the auditory nerve. A cochlear implant picks up sound using a microphone that transmits its

signal wirelessly to a receiver placed under the scalp, which in turn sends electrical impulses to electrodes implanted surgically in the cochlear, bypassing the eardrum and cilia altogether. In practice, however, things aren't so simple.

The microphone doesn't transmit audio signals directly to the scalp receiver. The sound is first passed to an audio processor, worn behind the ear or in a pocket. The processor attempts to filter speech from ambient noise and concentrate its perceptually useful content. This simplification is required because, while the cochlear contains tens of thousands of cilia for turning vibrations into nervous impulses, a cochlear implant has only a few dozen electrodes at most.

One electrode is enough to restore enough sound awareness to make a deaf person audibly aware of their surroundings, while a mere eight can restore the ability to understand speech, although it sounds rather mechanical. Listen to some simulated samples at www.bit.ly/n5nEy9.

No amount of electrodes can deliver more sound fidelity than the nervous system can normally handle. Still, while that could make cochlear implants unsuitable for people with long-term deafness, they may one day use external processing techniques to provide better-than-normal hearing to people with normal audio neurology.

SEEING IS BELIEVING

If electrically stimulating the auditory nerves is enough to generate sound, then doing the same to the optic nerve ought to generate vision. In fact, it does. This is the basis of the retinal implant, where opto-electrical sensors similar to those in digital cameras are used to convert light into electrical impulses that get sent straight to the brain.

Retinal implants use a small grid of electrodes that are implanted into the retina at the back of the eyeball. When different parts of the grid (loosely equivalent to pixels) fire an electrical impulse in a particular pattern, that pattern is picked up by the optic nerve and sent to the brain, which interprets the signal as visual information.

Retinal implants still require a functioning optic nerve to receive electrical signals, which rules out people who were born

blind and lack either an optic nerve, to receive the signals, or the neural pathways in the brain to process them. However, people with eye conditions that damage the retina progressively are ideal candidates.

The Argus II Retinal Prosthesis System from Second Sight uses a small digital video camera built into a pair of sunglasses to transmit images wirelessly to electrodes implanted in the retina. Second Sight doesn't disclose the camera resolution, but it's the number of electrodes that ultimately determines what a person 'sees'. Early implants used only four electrodes that provided little more than a sense of light and dark, but current implementations use thousands.

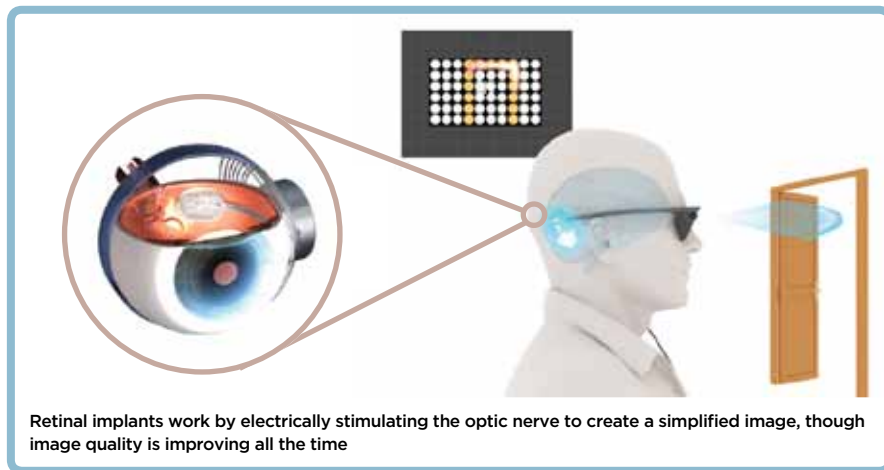
What the wearer experiences by having their optic nerve electrically stimulated in this way is unclear. Second Sight's Brian Mech explained, "We do not know exactly what the patient sees (that is hard, or perhaps impossible, to know). We can only measure what they can do. They are 'seeing' in the sense that the signal travels to the visual cortex and they literally 'see' the result of the stimulation. I think that, in the best patients, they perceive something like 'pixelated' images, like a low-resolution scoreboard."

Nonetheless, the visual information supplied to the brain by the Argus II is often enough to restore some spatial awareness, and perhaps even to read large print letters. The limitation with this implementation of the technology is that it delivers only a 20° field of view, which is equivalent to looking through a hole as wide as a 30cm ruler held at arm's length.

German company Retina Implant AG can manage only a 10° field of view with its retinal implant system, but this can be changed by moving the eye rather than the whole head. The opto-electrical sensor is implanted into the retina



▲ The Second Sight Argus II Retinal Prosthesis System uses a video camera built into a pair of sunglasses to transmit images wirelessly to the implant in the retina



Retinal implants work by electrically stimulating the optic nerve to create a simplified image, though image quality is improving all the time



◀ Increasing the number of electrodes in contact with the retina increases the image quality; these simulated images show the expected difference between four, 16, 64 and 1,500 electrodes

along with the electrodes, which also has the advantage of being more discreet.

As for using retinal implants to deliver superhuman vision, the problems are the same as with cochlear implants. If there is a limitation to the amount of information captured, it isn't down to the technology itself but the brain's ability to process it. This makes ultra high-resolution vision impossible. Still, it doesn't rule out the possibility of using zoom lenses and sensors that can detect more than just the visible spectrum of light.

GETTING A LEG UP

It's estimated that there are 1.7 million amputees in the US alone, and most of these have lost one or both lower limbs. Since even partial amputation of a lower limb can consign a person to a wheelchair and a life of dealing with associated health problems, there's considerable incentive to develop lower limb prostheses that restore as much normal function as possible.



The Otto Bock Genium bionic knee is hydraulically powered and can quickly react to its wearer's actions, so it can cope with different walking speeds and even stumbles

Because they rely on the rest of the body for power and movement, someone with just one functional lower limb prostheses can expend up to 40 per cent more energy than an able-bodied person when walking. The lack of control can also pose a problem. An able-bodied person uses muscles to flex and lock their knee when bending down, for example, and to adjust the position of their ankle and toes to cope with even ground, but a functional prosthesis can do neither.

How far a bionic lower limb prostheses can address these problems will depend on the degree of amputation. Research is currently focusing on limbs with both an active knee and foot. Vanderbilt University in Nashville, TN is a working one, and you can find details at www.bit.ly/oETbmX. However, the complex interaction between these two joints means that above-knee amputees are currently best served by a bionic knee alone.

Otto Bock has been developing bionic knees since 1997, and its recently launched Genium model is one of the most sophisticated available. Thanks to a built-in gyroscope and accelerometer (like those on an iPhone), plus software models for what constitutes normal gait, the Genium can play an active role in walking by flexing and extending automatically at appropriate times, removing the delayed 'drag' that functional prosthesis wearers complain about.

Abnormal events can be detected and dealt with, too. Tripping over a raised paving slab and putting a functional prosthetic lower limb forward for balance will result in a fall, since the mechanical knee joint locks only when in the fully extended position that happens mid-way through each step. The Genium, however, will sense that a stumble is taking place and lock the knee in whatever position it's in when weight is placed on it.

The calf muscle and Achilles tendon expend a significant amount of energy to kick the toes off the ground when taking a step. Take those away and the remaining leg has to pick up the slack, and the rest of body must cope with the increased stress this involves. The Genium knee's passive, but reactive, hydraulic mechanism doesn't change this, but only because the knee doesn't pay a



▲ A bionic knee behaves much like the real thing, which means the wearer doesn't have to worry about its position, or whether or not it can bear weight

▶ A functional prosthetic foot uses flexible components and shock absorbers to replace the function of the joints, muscles and tendons



major part in transmitting energy to the foot while walking. However, the ankle does, which is why the iWalk PowerFoot BiOM uses an active powered mechanism to make below-knee amputees more mobile.

Instead of using an Achilles heel and calf muscle to push the foot off the ground with each step, the PowerFoot BiOM uses a hydraulic piston for the same effect. As with the Genium knee, sensors detect what the wearer is doing and react in real-time, making the PowerFoot BiOM able to deal with uneven ground, inclines and stairs – all things with which functional lower limb prostheses struggle.

The iWalk's president and CEO, Tim McCarthy, reckons there is still much to be done to stream the design and improve battery life. Still, despite the PowerFoot BiOM only becoming commercially available in early 2011, it's already had a profound impact on the people using it. Once the final software tuning is performed over Bluetooth using an Android application, the usual reaction is that it feels natural, which is something of a rarity for any prostheses.

As for enhanced performance, the need to balance a bionic foot to work only as well as the remaining limb makes this difficult for unilateral (one limb) amputees. "When we fit the BiOM to a unilateral amputee, we're trying to mirror that individual's sound side to create symmetry," said McCarthy. "If we were trying to augment that unilateral, they would have the opposite effect where the prosthetic limb is outperforming the sound limb and secondary muscle groups need to accommodate it."

This is only an issue for people with one bionic lower limb. "We've got bilateral amputees with no sound side to mirror in this way," added McCarthy. "I've seen instances where we've adjusted the power components and they move a lot faster than an equivalent unilateral amputee."



EXOSKELETONS

For all their sophistication, prostheses still have to connect with the residual limb somehow. Most use a cuff into which the residual limb fits, which is obviously a weak point. Osseointegration, where a titanium peg is surgically implanted and biologically integrated into bone, offers a more permanent fixture, but it's only as strong as the part of the skeleton to which it's attached. A bionic arm may be capable of lifting a half-ton weight but the bone/titanium interface is not, nor is the rest of the human body.

One way around this is to bypass the human musculoskeletal system completely, which is what an exoskeleton does. Exoskeletons consist of powered upper and lower prostheses that attach to the wearer's existing limbs — think Iron Man without the armour plating. The technology is of particular interest as a way to allow stroke and spinal injury patients to walk. These are people who haven't lost a limb, but just can't use those they do have.

FRAME ACADEMY

Since exoskeletons use an external power source and are constructed from material that is far stronger than human tissue, they also offer a way to significantly enhance the capabilities of an able-bodied person, which is why the military is actively funding their research. With the weight taken by the exoskeleton itself, and batteries powering its powerful mechanical systems, the goal is to enable soldiers to lift heavy loads and travel over long distances with little effort. Being able to tear down a brick wall wouldn't hurt, of course.

▶ Raytheon's second-generation robotic suit is stronger, lighter and faster than the original XOS



▶ Exoskeletons could enable stroke and spinal injury patients to become mobile again by providing external power to their lower limbs



▶ Exoskeletons such as the Raytheon XOS 2 are the most promising technology for superhuman bionic abilities, since they augment existing function rather than replacing it completely



The iWalk PowerFoot BiOM has an hydraulic Achilles tendon, powered by a lithium-ion battery, that makes walking feel much more natural than with a traditional prosthesis

HANDY MAN

Bionic upper limb prostheses technology lags behind that of lower limbs, for one reason: there's less demand. Lower limb amputations outnumber upper limbs. Furthermore, upper-limb amputees can cope pretty well with one hand and around 20 per cent eventually abandon their prostheses. Problems with existing functional solutions obviously contribute to that figure, since the hand is a fiendishly difficult body part to duplicate mechanically, but recent bionic

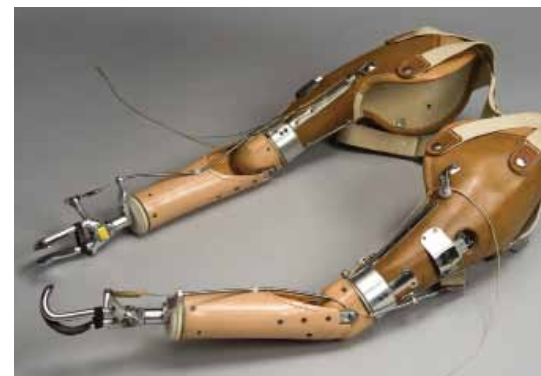
advances have produced some incredible results and UK company Touch Bionics leads the field.

Bionic hands have been available for some time, but models were little more than simple motorised grippers, and nowhere near as versatile as a real hand. The Touch Bionics i-Limb was the first to provide five fully articulated, independent digits. Still, offering the same range of motion as a real hand is one thing, but providing a way for the wearer to control it is something else.

Bionic limbs traditionally use 'myoelectric' sensors that stick to the skin of the residual limb and sense the electrical signals generated by the muscles beneath. Depending on the degree of amputation, the muscles may not be those that were originally used to control the missing part of the limb, so the wearer must go through a learning process. Touch Bionics supplies training software for this, and potential patients can use a wireless standalone version of the i-Limb to assess their suitability for the full prosthesis.

Myoelectric control may be unnatural at first, but the practice can soon 'rewire' the brain so the i-Limb wearer stops thinking about twitching a particular muscle and just thinks about moving the hand. Speaking on *BBC Newsnight*, i-Limb wearer Dr Bertolt Meyer likened this to the muscle memory that develops when learning to drive.

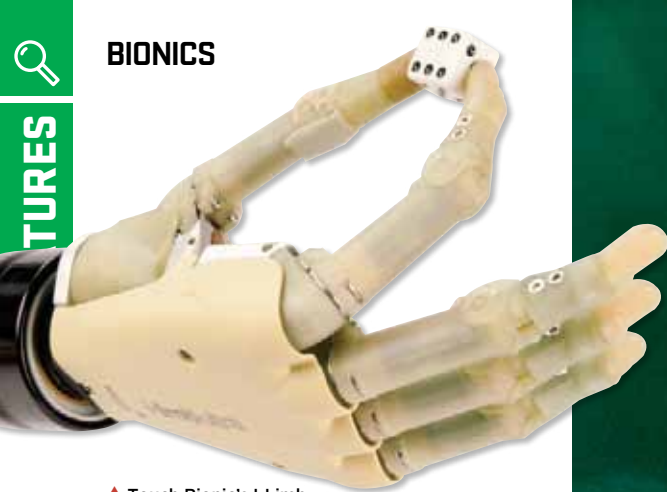
"When [I] first use a prosthesis like this, when I want it to open or I want it to turn, I have to



▶ A traditional functional upper limb prosthesis with cable-controlled split hooks for hands

flex [a particular] muscle. But over time, this intermediate step goes away. It proceduralises," said Dr Meyer. "It's like reverse parking. You don't have to think how to do it — you just do it."

As versatile as it is, the i-Limb's range of control is limited by being able to detect only four residual muscle actions. Touch Bionics thinks that future improvements in the control system will be possible through software upgrades. Still, myoelectric sensors aren't the only option available for bionic limb control, nor are they viable for people with certain upper-limb amputations.



▲ Touch Bionic's I-Limb Ultra was the first bionic hand to offer five fully articulated digits, so it worked – and looked – like the real thing



Touch Bionic's I-Limb ultra was the first bionic hand to offer five fully articulated digits so that it worked, and looked, like the real thing.

Targeted Muscle Reinnervation, or TMR, is a surgical procedure that redirects the nerves that remain after an upper-limb amputation, from inside the shoulder to the surface of the pectoral muscle in the chest. The limb they once controlled may no longer exist, but the brain isn't aware of that and so when the patient thinks about bending their non-existent elbow, those nerves – and now the corresponding area of the upper chest – will still react. Electrodes can then detect these nervous twitches and transmit them to a bionic limb to give a level of intuitive control that isn't possible with myoelectric sensors.

Unlike myoelectric sensors, TMR can also generate multiple, simultaneous signals. This means a patient can extend a bionic arm, rotate the wrist and open the palm in one fluid motion, when they want to shake hands, say. This kind of control is useful for complete-arm prostheses, such as the Luke arm being developed in the US

by Dean Kamen's DEKA (of Segway fame) as part of a \$100-million DARPA-funded project.

The Luke arm has an unprecedented 18° of motion (the human arm has 22°). It also has many other bionic innovations, including a modular design and vibrating motors that provide tactile feedback. Its complexity means that the wearer must use multiple controls, including buttons in each shoe. However, researchers at the Rehabilitation Institute of Chicago have successfully demonstrated TMR control of the Luke arm (see www.bit.ly/nrYloK) and are looking at targeted sensory reinnervation, which is a way of providing sensory feedback from the bionic limb to the nervous system.

ARE WE THERE YET?

Despite all the progress that has been made with bionic prostheses to date, there is much, much more to be done. For limbs, the goal is to

develop devices that mimic the real thing more closely in both form and function. This requires advances in hardware to create ever more robust and articulate limbs with increased battery life, and advances in software engineering to develop more sophisticated systems that can automate the same kind of fine control offered by the nervous system.

For sight and hearing, the limits of existing implant technology have yet to be reached, but there is still much to learn about how the brain processes information from these sense organs (particularly for colour perception, for example) and how it can be delivered more effectively by artificial means.

It may be another 40 years before bionic prostheses technology reaches a similar level of sophistication to that which Steve Austin possessed. Still, all indications are that it will be achieved within many of our lifetimes. **CS**

MEET THE TOUCH BIONICS MAN



Thirty-three-year-old Dr Bertolt Meyer was born without a lower left arm and has used several prosthetics since he was three months old. Dr Meyer was first fitted with a myoelectric prosthesis in 1999, but soon tired of its shortcomings. He was fitted with the Touch Bionics i-Limb in 2007, and in 2010 he became the first person to use the Bluetooth-enabled i-Limb Pulse.

CS Since you were born without a left hand, was it difficult for you to learn how to control the i-Limb given that you had no existing mental frame of reference for that particular limb?

BM I think it's easier to learn to how use a myoelectric prosthesis if you had a hand that was amputated. I didn't really have a mental representation of a left hand in my body image and it took me over three months to learn how to use the muscles that activate the myoelectric sensors, because I had never used them in my life. The I-Limb uses muscles that would normally flex the wrist of a hand I never had.

CS You use four different automated grip patterns, with some manual repositioning of the hand to achieve a few more. Is this number limited by your ability to send different signals, or because you only need four basic grips?

BM I only need my other hand to reposition the I-Limb thumb. The actual switching between grip patterns happens via the signals coming from the electrodes attached to my forearm. The i-Limb can only understand four different control signals: a muscle co-contraction

(where both electrodes fire simultaneously), a double impulse on the opening electrode, a triple impulse on the opening electrode, and a prolonged opening signal that lasts for more than two seconds. That's where the limitation comes from – these are the only special triggers the hand understands. I can't think of any other signals that would make sense. Special signals on the closing electrode could cause the hand to switch into a different grip when it's holding something, with potentially dangerous consequences. For safety reasons, the hand only 'listens' for the special signals when it is fully open.

CS The i-Limb has technology for controlling the strength of a grip, but is the lack of sensory feedback from the prosthesis a problem for certain circumstances?

BM Of course the lack of sensory feedback is a problem. You always have to see the hand in order to know what you are doing or holding and so must rely upon visual feedback. Therefore, you can't use a prosthesis for taking something out of a large bag, for example, because you can't feel what the hand is touching.

CS Is there anything you wish the i-Limb could do that would improve it immeasurably for you?

BM Two quite basic things, actually. I'd like it to move faster, as it is quite slow, and I'd like it to make less noise. In a quiet room such as a meeting room, its movements produce an audible noise that attracts everyone's attention – and that can be annoying.