

# Clinical review

## *Science, medicine, and the future* **Artificial limbs**

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In recent years technical innovations have combined to make artificial limbs much more comfortable, efficient, and lifelike than earlier versions. Future innovations are likely to depend on the interaction between three powerful forces—amputees' demands, advances in surgery and engineering, and healthcare funding sufficient to sustain development and application of technological solutions. This article looks at the innovative new prostheses that are currently available and discusses future developments.

### Methods

This paper is based on the clinical experience of the authors in Britain and the United States, a review of the literature, and information gathered from colleagues in rehabilitation medicine throughout the world.

### Amputation: causes and impact

In developed countries the main cause of lower limb amputation is circulatory dysfunction. The prime reason for this is atherosclerosis, although up to a third of patients have concomitant diabetes. These people are usually in their sixth decade (or older), and most have additional health problems that limit their walking ability. In the United Kingdom there are about 5000 new major amputations a year.<sup>1</sup>

This is in sharp contrast with developing countries, where most amputations are caused by trauma related either to conflict or to industrial or traffic injuries. Global extrapolations are problematic, but a recent US study states that the amputation rate among combatants in recent US military conflicts remains at 14-19%<sup>2</sup> and the devastation caused by land mines continues, particularly when displaced civilians return to mined areas and resume agricultural activities.<sup>3</sup>

An amputation is a permanent disfigurement. For some, the relief from pain or disease in the affected limb may be welcome, but, for those losing a sound limb, resentment is understandable. Despite modern prosthetics, some adaptation is required, and people vary in their ability to adjust to the change in body image and, sometimes, lifestyle.

### Advances in prosthetic technology

Prosthetic technology has advanced to a remarkable degree in the past two decades, driven largely by

### Predicted developments

Direct skeletal attachment (osseointegration) of prostheses may be a routine option for some amputees

Amputee demand for more versatile, higher performance prostheses with more lifelike external coverings will fuel further innovation

The use of prostheses controlled by microprocessors to allow finely tuned movement will increase

Future use of new prosthetic components is liable to be controlled by funding constraints in both developed and developing countries

amputees' demand. Today, otherwise healthy individuals with mid-calf amputation should be able to participate in a full range of normal responsibilities, to walk without any perceptible limp, and to engage in recreational and sports activities.

### Interface between stump and socket

The single most critical aspect of any prosthesis is the quality of the interface between the limb remnant (stump) and the artificial prosthesis. The portion of the prosthesis that fits snugly over the limb remnant, the "socket," determines the amputee's comfort and ability to control the artificial limb. Since the 1980s prosthetic clinicians and researchers worldwide have made breakthroughs in design and materials that have greatly improved the connection between the socket and stump.

Currently, silicone elastomers are widely used to create a soft and slightly elastic inner liner, providing a thin, comfortable, and compliant barrier between the amputee's skin and the more rigid, weight bearing portions of the prosthetic socket.<sup>4,5</sup> These socket liners, are usually tethered to the inside of the socket with a mechanical device, termed a shuttle lock, to provide suspension for the prosthetic limb. To remove the artificial limb, the amputee simply presses a concealed button, disconnecting the liner from the socket.

In recent years researchers have developed a variety of thicker gel materials that add a measure of

cushioning and pressure dissipation while retaining the benefits of the original liners (fig 1). The same gel cushioning technology has also been adapted to bicycle seat coverings and similar non-prosthetic applications.

#### Dynamic response feet with plastic springs

Carbon fibre composites, developed by the aerospace industry, are increasingly being used in artificial limbs, largely because of their superior strength to weight characteristics. One of the most successful innovators has been Flex-Foot, founded by US researcher and amputee Van Phillips. By the 1990s, Flex-Foot's prosthetic foot designs based on carbon fibre springs were widely acknowledged to be the most effective at storing and releasing energy during walking and, in particular, recreational and competitive sports activities.<sup>6-8</sup> The combination of enhanced socket comfort and prosthetic feet with dynamic response enable amputee medallists in the Paralympics to complete the 100 metre dash within about one second of the Olympic record.

#### Shock absorbing mechanisms to reduce impact forces

Once amputees worldwide began to regularly jog, run, and jump, it became apparent that the lack of shock absorption in artificial limbs was a limiting factor. Flex-Foot introduced the Re-Flex shin-foot design in 1993, coupling a spring loaded shock absorber with the dynamic response foot (fig 2). Recently, gait studies have confirmed that this type of component improves the biomechanical performance of artificial limbs, which may explain the enthusiastic acceptance of such devices by non-athletes too.<sup>9</sup>

Until this past decade, thigh amputees have been forced to hold their prosthetic knee in full extension throughout most of the stance phase of the gait cycle to prevent the leg from collapsing. This not only results in an unnatural gait but also eliminates the primary mechanism for shock absorption offered by the biological knee. To address this shortcoming, a growing number of prosthetic knee designs now include a "stance flexion feature." The UK company Blatchford was the first to offer this capability, termed the "bouncy knee."<sup>10</sup> As the amputee bears weight on the limb a friction brake engages automatically and stabilises the knee, while a small rubber element allows a few degrees of motion to absorb shock and simulate knee flexion during the early stance phase.

#### Microprocessor controlled movement

The first artificial knee with an "on board" computer to improve the symmetry of amputees' gait across a wide range of walking speeds was developed by Blatchford in the early 1990s. Studies have confirmed that these "intelligent prostheses" offer amputees a more reliable gait pattern during the swing phase of the gait cycle, permitting them to walk with more confidence and in a more energy efficient manner.<sup>11 12</sup>

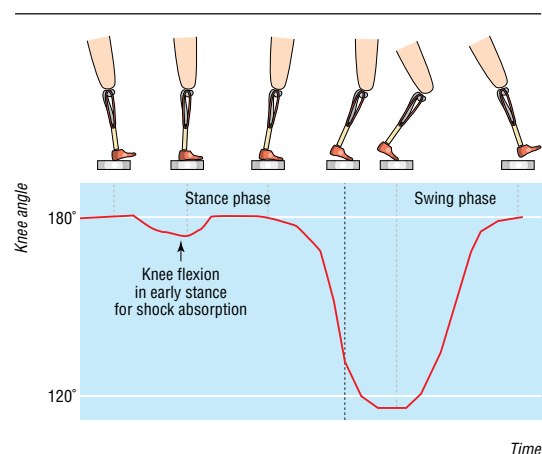
The Otto Bock C-Leg takes this a stage further, offering not only symmetry in the swing phase but also markedly improved security in the stance phase—that is, the knee will not buckle unintentionally during standing (fig 3). Sensors in the ankle and shin of the prosthesis continually assess the position of the leg in space as the amputee is walking. The data are fed into



**Fig 1** Rather than using cumbersome belts and hinges, today's prostheses may be suspended via a cushioning sleeve that the amputee rolls on to the limb stump. In this example, a serrated pin at the end of the liner automatically locks into the prosthesis when the amputee stands. To remove the prosthesis, the amputee depresses the release button on the medial aspect of the artificial leg. (Picture courtesy of Otto Bock)



**Fig 2** The Re-Flex prosthetic shin-foot assembly, made from high strength carbon fibre composite materials, includes a spring loaded shock absorber and flat springs in the foot that help propel the leg forward during walking and sporting activities. (Picture courtesy of Ossur)



**Fig 3** Advanced prosthetic knees allow a controlled amount of flexion during initial weight bearing (stance flexion) to simulate a more normal gait pattern and to absorb some of the impact of walking on an artificial limb. (Picture courtesy of Otto Bock)



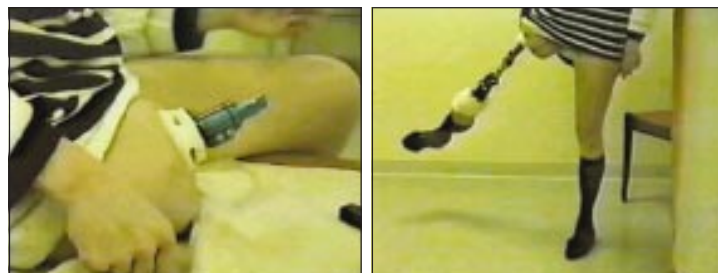
**Fig 4** The Otto Bock C-Leg with computer controlled knee and integrated motion and force sensors to optimise hydraulic damping, making both walking and stair descent easier. (Picture courtesy of Otto Bock)

two microprocessors inside the knee, and the resistance from a hydraulic damper is adjusted up to 50 times a second, optimising knee stiffness throughout the entire gait cycle (fig 4). The ability of this knee to automatically increase knee stability within micro-seconds makes it much easier and safer for amputees to traverse uneven ground, to walk on sloped surfaces, and to walk down stairs.

Preliminary studies report that amputees have increased independence with such a responsive and stable electronic prosthesis, confidently tackling more difficult and varied activities than they did with other limbs.<sup>13 14</sup> Based on the widespread success of more than 1000 C-Leg fittings to date, the clinical application of such prostheses with microprocessor control of stance and swing is expected to increase steadily. Such technology costs about four times as much as limbs with mechanical knee controls.

### Skeletal attachment of artificial limbs

Several decades ago, the Swedish physician Per Brånemark astounded the dental profession by developing a surgical technique to permanently anchor artificial teeth into the jaw. Despite numerous outcries about the futility of such efforts at the outset, his methods



**Fig 5** Swedish experiments suggest that direct attachment of prosthetic limbs into the remnant bone may be feasible and offers better control, comfort, and sensory feedback.

are now accepted worldwide as a routine method of dental restoration. In the past few years he has turned his attention to achieving similar results for upper and lower limb amputees and has generated similar controversy.<sup>15</sup> Preliminary results, and enthusiastic feedback from participating amputees, justify further exploration of this technique (fig 5).

If these prostheses prove successful long term (at least 10 years) direct attachment of an artificial limb to the skeleton may avoid difficulties inherent in creating custom-designed prosthetic sockets, where fitting comfort depends on volumetric matching to the amputation stump. Being a dynamic organ, the stump tends to shrink (atrophy) over time, though it may also swell with heat or weight gain, which can lead to chafing. With osseointegration, the prosthesis fit is unaffected by such volume changes.

The drawbacks of this technique are that it requires two stage surgery to attach the titanium implant to bone. The procedure carries the risk of osteomyelitis or infection at the abutment of the implant, and meticulous personal hygiene is a prerequisite in patient selection. On a practical note, the typical Western person with a lower limb amputation, elderly and with poor circulation, is not likely to be a candidate for such an involved surgical procedure. It is primarily the subset of younger individuals, often with traumatic amputations, for whom this technique holds the greatest promise.

Comparative trials of the technique are not possible. To date, the patients selected for the procedure have had high level, above knee amputations for which all other prosthetic fitting techniques had failed. However, three year follow up of several dozen participants suggests that amputees with an osseointegrated prosthesis quickly develop superior control over the limb, at least in part because of enhanced sensation, termed “osseoperception” by Brånemark. This combination of increased comfort, perception, and control is expected to drive the next round of technological innovations, just as superior socket designs did previously.

### Making artificial limbs lifelike

Although some amputees like the robotic appearance of prosthetic components, most prefer a limb that is lifelike and therefore inconspicuous. The same silicone materials that contribute to socket comfort have also been used to create incredibly realistic external coverings for both upper and lower limb devices.

The present state of the art is the creation of a carefully sculpted match for the opposite limb, with individual colouring to give a lifelike finish.<sup>16</sup> Unfortunately, such custom made prosthetic “skins” are costly (about £2500 (\$3500)), particularly since they need replacement after a few years because of unavoidable wear and tear from normal use.

Silicone is also a relatively heavy material, so the search continues for a lightweight alternative, ideally offering greater flexibility and durability. Because of the costs involved, most amputees currently receive “semi-custom” external coverings that are mass produced industrially from less expensive materials and provide only a generic external appearance.

## The potential of low cost, limited function prostheses

Modern industrial fabrication, particularly with injection moulded plastics, can create lightweight, low cost components with sufficient function for limited walking, and this might be quite sufficient for today's typical elderly amputee. Some designs may also be made moisture resistant and therefore suitable for use in the shower or on the beach. The lower manufacturing costs of such devices may permit their use in developing economies, where the cost of more complex technology is prohibitive. The Shower Limb, developed by Blatchford, is an example of this trend. The company has also developed a special line of plastic Atlas Prostheses designed specifically for use in tropical climates.

The International Committee of the Red Cross has established an initiative to produce low cost polypropylene plastic prostheses, made by unskilled local workers, for areas where conflict or environmental catastrophes have resulted in large numbers of traumatic amputations (see [www.icrc.org](http://www.icrc.org)). These devices are well accepted clinically, although some problems have been reported with their durability.<sup>17 18</sup>

## Future developments

The future development of prostheses will depend greatly on demand. The market for low cost, limited function devices will continue to expand in an effort to meet the needs of the developing world as well as the funding restrictions that are increasingly common in all economies. At the same time, innovative technologies will continue to be adapted from the aerospace and computer industries and applied to high performance artificial limbs whose function will more and more closely approximate to the missing limb.

Initially, prosthetic innovations are often used sparingly, primarily by amputees with private funding—particularly those who are competitive athletes. As experience is gained, manufacturers discover how to apply the same principles to moderate cost devices intended for less active individuals, and the performance of prostheses in general will gradually improve as a result.

Similarly, some of the newer materials and applications will be used for the benefit of amputees in developing countries, despite differences in the cause of amputation and people's needs. It is really financial constraints that limit the rate of advancement in prosthetic rehabilitation, and one of the greatest challenges for the new millennium will be to find the will and the way to fund widespread application of prosthetic innovations.

Competing interests: JWM has been employed by Otto Bock. Since 1999, he has been an independent consultant in prosthetics and orthotics and therefore may have a consulting relationship with any of the companies mentioned in this article. He has received payment for organising educational programmes, speaking, or consulting from Otto Bock and from Flex-Foot, which was recently acquired by Ossur.

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## Corrections and clarifications

### *Life expectancy rates show health inequalities*

In this news article by Lynn Eaton (1 September, p 471) some of the data accompanying the map of life expectancy rates in Britain were wrong. For the lowest five health authorities we inadvertently listed (and showed on the map) the authorities ranked 10 to 5 in the lowest 10. The lowest five authorities are in fact: for men, Manchester 70.2, Greater Glasgow 70.4, Western Isles 70.9, Argyll and Clyde 71.2, Liverpool 71.7; and for women, Greater Glasgow 76.5, Manchester 76.6, Liverpool 77.0, Lanarkshire 77.3, Argyll and Clyde 77.7. The text in the article was correct.

### *The public health benefits of mobile phones*

Owing to a misunderstanding, we raised the status of Debbie Lawlor, the author of this Filler piece (25 August, p 447), to senior lecturer, whereas she is in fact a lecturer. Thanks to Dr Lawlor for alerting us to this.