Bionic prosthetic hands: A review of present technology and future aspirations

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Review

Bionic prosthetic hands: A review of present technology and future aspirations

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ABSTRACT

Background: Bionic prosthetic hands are rapidly evolving. An in-depth knowledge of this field of medicine is currently only required by a small number of individuals working in highly specialist units. However, with improving technology it is likely that the demand for and application of bionic hands will continue to increase and a wider understanding will be necessary.

Methods: We review the literature and summarise the important advances in medicine, computing and engineering that have led to the development of currently available bionic hand prostheses.

Findings: The bionic limb of today has progressed greatly since the hook prostheses that were introduced centuries ago. We discuss the ways that major functions of the human hand are being replicated artificially in modern bionic hands. Despite the impressive advances bionic prostheses remain an inferior replacement to their biological counterparts. Finally we discuss some of the key areas of research that could lead to vast improvements in bionic limb functionality that may one day be able to fully replicate the biological hand or perhaps even surpass its innate capabilities.

Conclusion: It is important for the healthcare community to have an understanding of the development of bionic hands and the technology underpinning them as this area of medicine will expand.

Introduction

The human hand is able to perform a complex repertoire of sophisticated movements that enables us to interact with our environment and communicate with one another. The opposable thumb, a rarity in nature, has helped us achieve high levels of dexterity allowing our evolution to proceed rapidly over other creatures. To perform complex hand movements we need to synthesise an enormous amount of somesthetic information about our environment including fine touch, vibration, pain, temperature and proprioception.

The sensory and motor cortices span large, complex areas of the brain and are devoted to interpreting the vast sensory input and using it to fine-tune the motor control of over forty

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separate muscles of the forearm and hand. This delicate, sophisticated arrangement allows us to perform precision activities such as writing and opening doors whilst simultaneously avoiding noxious stimuli.

Loss of a hand can be devastating and unlike losing a leg the functional limitations following hand loss are catastrophic. The primary causes of hand loss are trauma, dysvascularity and neoplasia.[1] Men are significantly more likely than women to lose their hands with 67% of upper limb amputees being male. Upper limb amputations most commonly occur during the productive working years with 60% between the ages of 16 and 54. The functional demands in this patient group are high and their expectations of a prosthetic limb mirror this.

A few hundred years ago a hand amputee would have been condemned to a hook prosthesis that had limited function and carried significant social stigma. However in today's society a hand amputee can expect a replacement hand that replicates a whole host of normal hand functions and looks remarkably life like. Significant advancements in bionic hand technology have occurred and this field is now considered to be a triumph of medical engineering excellence.

The alternative option to a bionic hand is a hand transplant, which was first performed in 1999.[2] There have been successes in this field but there are major drawbacks to the widespread use of transplantation. The requirement for a donor limb that matches the recipient in terms of size and shape mean suitable donor limbs are rare.[3] The recipient's reliance on long-term immunosuppression and the complexity of transplant surgery are likely to limit transplantation as the major reconstructive option for amputees.[4] Therefore the more widespread option for an upper limb amputee is to opt for an artificial replacement.

The modern prosthetic hand has been designed to closely approximate the natural limb in both form and function.[5] Despite the fact that the bionic hand was recently hailed as a triumph of engineering excellence[6] it remains an inferior replacement to the real thing and consequently there are a number of barriers to its uptake amongst the upper limb amputee population. These prevent the prosthetic hand from achieving the ultimate goal of any prosthesis: 100% acceptance by its users.

So, how close are we to creating an artificial hand that is a perfect replica of the real thing? Can we expect that medical and engineering advancements will continue to improve upon nature and eventually deliver a bionic hand that enhances our strength, speed and abilities far above human norms? Will we all be like the Six Million Dollar Man or the Bionic Woman one day?

Patient acceptance

Older robotic design bionic arms could not be attached to the body. Instead, they had to be mounted on a desktop or chair. They were heavy and cumbersome with a variety of control input devices such as voice input or computer control that were unacceptable to many users. Currently available bionic hands are able to achieve a better range of functional grips including key, power, precision, index point and thumb park that confer far wider application of the replacements than previously achievable.[7] The drawback is that extensive training with occupational therapy input is required to achieve successful function[8] and despite this even the best bionic limbs still do not come close to replicating the complex intrinsic functions of the innate hand.

Servicing bionic limbs requires specialist input and often requires the affected component to be sent back to the manufacturer. Introduction of modular components such as the iLimb Hand (Fig. 1)[9] allow the individually powered digits to be removed for servicing so that the user can maintain some functionality with the remainder of the limb intact. Development of modular components has also meant that prosthetic replacements can be custom adapted for partial hand amputees that were previously unavailable.

The perceived stigma arising from use of a prosthetic hand has been considerably reduced because of aesthetic improvements. Commercially available coverings range from the life like to the futuristic. Coverings have been developed which can closely approximate the natural skin tones and appendages of the wearer or alternatively they can allow visualisation of the metallic infrastructure beneath which is especially popular with military personnel. However the durability of the coverings requires diligent care and adds further costs to the prosthesis.

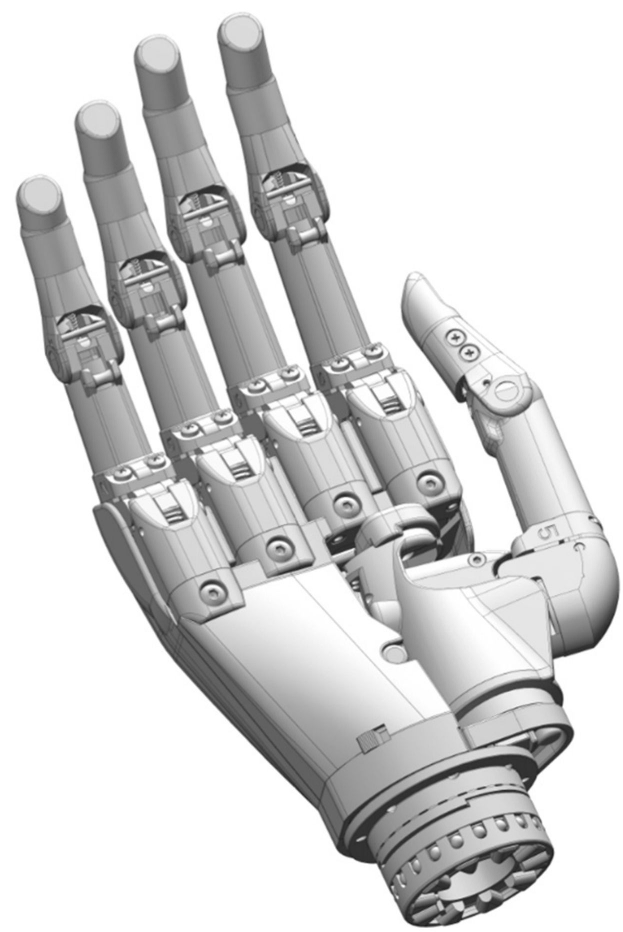

Fig. 1 – An illustration of the iLimb hand as an example of a modern prosthetic hand demonstrating the modular assembly and aesthetic appearance of currently available prostheses.

The natural hand does not make any noise during movement in contrast to bionic limbs that rely on motors to power the digits. The noise generated during movement can be distressing to some users but it is hoped that future developments such as hydraulic powered motors will be able to reduce noise to a minimum.

Advances in biomaterials have begun to reduce the weight of bionic hands, which has historically been a barrier to uptake amongst amputees. Small reductions in the weight of bionic hands make a big reduction in the effort required to manipulate them because they sit at the end of a long lever arm. It is hoped that materials will soon be developed that are suitable for direct fixation to the bone allowing considerable reductions in the weight of the constructs and conferring additional strength to the limb.[10] The additional strength provided by fixation to bone could also address the inability to weight bear through the prostheses, which is seen as one of their major disadvantages. This function would be especially useful for bilateral limb amputees who need a limb strong enough to allow them to transfer from the sitting to the standing position.

Motor driven bionic limbs rely on a power source and being plugged in at the mains is not a realistic option. Improvements in battery life and the development of increasingly efficient actuators that are able to deliver higher forces for a given energy consumption have been advantageous for most limb users who employ their prosthetic hand for at least 8 h per day.[10] Further advances in battery life are required to prolong the time between charges but in the meantime practical solutions such as the ability to charge the devices from a car charger socket are being utilised. Perhaps a future goal should be to find a way to intrinsically power the bionic limbs negating the need for charging altogether?

Motor control

The human hand is by nature so complex that replicating its functions using a bionic device is a significant challenge. Controlling a bionic limb must be quick, easy and reliable for it to have any advantage over a non-functioning alternative.

The most basic, controllable, artificial limbs rely on a system of cables attached to a harness that the user wears. Motion of the residual limb relative to the patient's body controls the movement of the prosthesis. These limbs require the user to have enough strength to operate them and they are limited to a small repertoire of movements. However they are cheap to produce and are relatively easy to use, so they can be a suitable option for people with low demands.

Achieving a more complex set of movements relies on integration with a digital control method. These can be very basic, such as placing a controlling unit into the user's shoe, or very complex such as myoelectric control that interprets electrical activity in the neuromusculature of the limb stump to allow motion.

Myoelectric control is the most widely used method of control in commercially available bionic limbs. It relies on complex algorithms to make sense of the massive amount of electrical activity in the stump, which is affected by everything from movement in the shoulder or elbow to the heartbeat.[11] Techniques such as electrical pattern recognition can be used to activate whole muscle groups that form components of certain movements. For instance electrical activity in the flexor compartment of the forearm will lead to flexing of the bionic hand. Nevertheless learning how to use a myoelectrically controlled prosthesis can be time consuming and difficult and there must be enough electrical activity in the limb stump for them to work. Improving the accuracy of computer algorithms that decode the signals is a substantial area of research at present.[12–15]

Central and peripheral motor and somatosensory pathways retain significant residual connectivity and function for many years after limb amputation and this property has been exploited by researchers using a technique called targeted motor reinnervation to increase the accuracy of myoelectrically controlled prostheses.[16]

In this technique the nerves that once supplied the amputated limb muscles are surgically anastomosed into the remaining muscles of the amputation stump to create independently controlled nerve-muscle units.[17–19] The reinnervated muscles act as biological amplifiers of motor commands in the amputated nerves and the surface electromyogram (EMG) can be used to enhance control of a robotic arm.[20] This technique has shown promising results with the ability to achieve intuitive control of multiple functions in a bionic hand.[21,22]

An alternative system being developed to increase accuracy of myoelectric prostheses involves the implantation of bipolar differential electromyographic (EMG) electrodes within the muscle to create a system capable of reading intra muscular EMG signals that increases the number of control sources available for prosthesis control.[23,24]

Sonomyography is an alternative method of limb control being developed that utilises ultrasound to measure the change in size of contracting muscles in the stump.[25,26] This technique shows potential to increase the accuracy of movements and force calculations compared to the present day myoelectric systems.

The ultimate goal is to achieve a "Biomechatronic design" where the mechatronic system of the artificial hand is inspired by and works like the living limb.[27] To achieve this goal there would need to be integration of the prostheses with the central nervous system so that the replacement moves and is perceived as if it were the natural hand without the requirement for any training or adaptation.

The use of intraneural electrodes is perhaps the most promising technology that may hold the key to successful integration of bionic limbs into the biological system. Intraneural electrodes interface directly into the nerves in the limb stump and have the ability to carry a bidirectional flow of information between the bionic limb and patient.[28–30] There are still many obstacles to overcome before this technology is commercially available but it is hoped that it will eventually be advanced enough to allow limb amputees to be given bionic limbs that act and feel like the innate limb.

Sensation

Our hands allow us to interact with our environment. We use the sensory input for touch, to fine-tune movements and to avoid harm. A continuing challenge for prostheses developers is to replicate the sensory function of the hand. Sensation in a bionic limb can be divided into two distinct categories – sensory information interpreted by the device itself and sensation that is perceived by the user.

Modern units have developed simple techniques for interpreting tactile sensory information that the devices use intrinsically to modify their activity. For example information on grasp strength ensures a user will not break objects by holding them too tightly whilst information provided by detection of sound from microphones embedded in the hand ensures that the object will not slip out of the grip and be dropped.[31,32] This information, required for direct control of the device, can be interpreted via a low-level control loop thus decreasing the cognitive load of the user and increasing patient acceptability. These features improve the functionality of the device but do not provide the user with any sensory information about their surroundings.

Providing a sensory input from a bionic limb that is capable of being perceived by the user is far more complex. One approach is to utilise the concept of multimodal plasticity where loss of one sensory modality can be compensated by another.[33] For example hearing can partly compensate for the loss of touch if auditory feedback is given when a bionic limb comes into contact with an object.[34]

Another approach is to try to replicate sensation by transferring stimuli from electronic sensors in the bionic limb to natural sensors on the skin of the limb stump which the patient perceives as coming from the amputated limb.[35,36] This has been difficult to achieve but recent work has successfully replicated more complex sensory modalities such as cutaneous proprioception alongside fine touch and pain sensation.[36] It is hoped that this technique can be further developed to provide a complete range of sensations.

Direct interfaces with the peripheral or central nervous systems may provide the solution to enhanced sensation from bionic hands and ultimately come closest to restoring the original sensory perceptions of the hand.[37] The use of intraneural electrodes that are capable of delivering information directly to the peripheral afferent nerves within the residual limb has shown promising results in delivering meaningful sensations to amputees.[28] Delivering sensations through this approach has been shown to improve control as it allowed amputees to control the grip force and joint position of their artificial limb more accurately without relying on visual input. One of the main advantages of a sensitised bionic limb is the accelerated rehabilitation program as the patient finds it more intuitive to learn how to control when they are receiving tactile feedback from the device.[38]

With advancements in these technologies we may soon be able to re-wire the sensory input to the peripheral nervous system so that the central nervous system can perceive sensations coming from a bionic limb as if it were the natural limb.[37,39]

Conclusion

The prosthetic hand of the middle ages was present merely as a prop. Today we have bionic hand prostheses that give much better functionality, are acceptable to more patients and are durable and comfortable. However these prostheses still have to overcome considerable hurdles in order to mimic or even improve upon the intrinsic hand and they carry significant economic implications. The advancements in this field of medicine are exponential and it is likely that within 10 years there will be commercially available limbs that provide both sensation and accurate motor control from day 1. The progress to bioartificial organs that are fully integrated into the central nervous system and have capabilities that surpass our own may still sound more like science fiction than science fact but can cohesive work between medicine, engineering and materials science make the 6 Million Dollar Man a reality?

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