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Review Article

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The Bionic Human: A Review of Interface Modalities for Externally Powered Prosthetic Limbs

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Abstract

Background: The loss of a limb is a debilitating incident and can leave patients significantly disabled and often unable to perform activities of daily living. Prosthetic limbs can provide some modicum of normalcy back to their lives, and there has been much research over the past few decades into restoration of biomedical and physiological function with the use of externally powered and robotic prostheses. This review aims to explore the various approaches to machine-body interfacing that can be employed to achieve intuitive and meaningful control of these complex devices, and to discuss the individual benefits and drawbacks of each method.

Methods: Studies looked at include both primary and secondary sources of research. Identification was via a PubMed search for the terms "prosthetic limb", "powered prostheses", "myoelectric prostheses", "neural interface", "prosthetic somatosensory feedback", and "brain-machine interface", which resulted in a total of 3892 papers retrieved. Of these, 28 were retained as sources for this review. Selection was based on relevance to control of powered prostheses.

Summary: Significant strides have been made in expanding the choice of interface sites for bionic prosthesis control. Muscles, nerves, and the brain are all options, each with varying degrees of invasiveness and corresponding resolution of information obtained, and non-muscle interfacing prostheses may soon be commercially available. These advances have allowed for increasingly precise control of prosthetic limbs. However, this is limited by the challenge of returning sensory information from the prosthesis back to the user.

Introduction

Prosthetic limbs are artificial constructs that are attached in some way to the body of the user with the purpose of restoring at least some function of a lost or nonfunctional appendage. A bionic prosthesis is one that uses electrical signals from the body to move parts of the powered artificial limb. The most prevalent application of modern prosthetic limbs is the rehabilitation of injured soldiers who have lost limbs in the line of duty. A tragically common event, between 2003 and 2014, over 260 British soldiers in Afghanistan had to have amputations, with most having multiple limbs removed (1). However, amputation is not the only mechanism of functional limb loss. Traumatic spinal cord injuries and certain degenerative diseases often leave patients unable to move or sense their limbs. The ideal bionic limb would be able to reproduce all the functions of the limb that that these patients have lost. This includes all of the degrees of freedom of movement and somatosensory feedback to the user in all the modalities provided by a physiological limb. Furthermore, the prosthesis needs to be able to operate in all of the conditions a normal limb would, such as extremes of temperature and rain (2). The term "degree of freedom" in the context of this review is a plane of movement. For example, the upper limb, excluding the fingers, has a total of 7 degrees of freedom: 3 for the shoulder, 1 for the elbow, and 3 for the wrist.

Modern Prostheses and the Body-Prosthesis Interface

The key component of all prosthetic limbs, as well as all prostheses in general, is the interface between the user's body and the prosthesis. It is at this point that information can be exchanged between the user and the prosthesis, allowing purposeful movement of the limb and sensory feedback to the user. Classification is based on the site of interface. Body-powered prostheses are the oldest type and not considered bionic: they have existed for centuries and are simple pulley mechanisms where flexion and extension of an existing joint cause corresponding movement in the prosthetic distal joint. Myoelectric interfaces use signals from the remnant muscles to control the prosthesis. Peripheral nerve interfaces utilise signals directly from nerves within the limb. Lastly, central nervous system (CNS) interfaces derive their information directly from the brain motor cortex. The amount of information that can be obtained (and therefore degree of control) is often dependent on the level of amputation. For example, it would be difficult to allow control of individual fingers in upper limb prostheses if the limb has been lost at the shoulder. However, if only the hand or distal forearm has been lost, fine control of fingers may be achieved, since many of the muscles and nerves that control the fingers in a normal limb are still present (2).

Another crucial aspect of the use of a prosthesis is the mechanism of attachment to the body of the user. In the past, the only way to achieve this was to use a harness that held the prosthesis against the limb stump. While harnesses are still widely used, particularly amongst users of passive prostheses, there are other options available today. Modern attachment mechanisms include suction sockets, elastic suspension sleeves, and osseointegration of the prosthesis. A suction socket is made of silicone and grips the remaining limb stump, while also being attached to the prosthesis (3). Elastic sleeves were developed as an alternative to suction sockets. They grip the stump due to their elastic property and are used to attach more lightweight prostheses. Osseointegration is the newest and most complex attachment mechanism, involving integration of the prosthesis with the remaining bone of the limb. This is done by drilling into the bone and screwing in the housing for the prosthesis. Unlike other methods of attaching the prosthesis, this is an invasive method involving implantation of foreign material into the patient's body. As such, there is a far greater risk of infection and other adverse reactions to the implanted part of the prosthesis, as well as the risk of damage occurring to adjacent structures during the procedure. While studies indicate low rates of infection among patients who have had the osseointegration procedure, the risk is still higher than with noninvasive attachment techniques (4). Nevertheless, osseointegration has several advantages, the first of which is that it is the most naturalistic of all the methods and reduces the discomfort experienced when prostheses are used for long periods of time. Furthermore, as this process allows a permanent fixture to be available for prostheses to attach to, it can also provide a permanent site for interfacing the body and prosthesis. An example of this could be a peripheral nerve interface to nerves near the integration site, allowing both control and somatosensory feedback (5).

Myoelectric Interfaces

Myoelectric prostheses work by using information from remaining muscle to imitate their function and exercise control over the prosthetic. The information gathered is in the form of the electromyographic signals, which are caused by the generation of electrical potential within skeletal muscle cells during contraction. This information is gathered by surface electrodes, which then activate corresponding motors within the prosthesis that initiate movement, such as flexion/extension of the elbow and wrist and rotation of the latter (6). Currently there is only one pair of sensors in commercially available myoelectric prostheses, but multichannel sensors are being investigated to allow greater control (7). However, the activation of the motors is not homologous to muscle groups that perform the corresponding movement in a normal arm. As such, the information from the electrodes must be processed using certain algorithms, which attempts to recognize the movement that the user is trying to perform. However, this system is not entirely intuitive and therefore must be practiced and learned. This was the earliest bionic prosthesis type developed, and this was accomplished by scientists in the USSR in 1958 (8). As such, it is the only interface used in commercially available bionic prostheses; all other types are still experimental.

However, it is often found that the muscles that remain after loss of a limb are insufficient to allow precise control of a prosthesis For example, if an arm is lost at the level of the shoulder, only a few upper limb muscles like the deltoid and pectorals will be available as sites for EMG detection, and this is not sufficient to allow utilisation of prostheses to perform complex movements or fine motor functions. A solution to this problem is Targeted Muscle Reinnervation (TMR). In TMR, the remaining nerves of the lost limb are surgically sited to separate locations within the residual muscles, with different nerves reinnervating different parts of the muscle. The signal from these nerves can then be picked up from the specific area of muscle that they reinnervate. The original nerves supplying this muscle are often removed if the action of the muscle is no longer needed. This procedure allows for natural amplification of the EMG signal, which allows for control of high degree-of-freedom prostheses without using invasive interfacing techniques and incurring the complications they are associated with. Furthermore, because the nerves that are used during operation of the prosthesis can be translocated, this allows for the patient to make movements of the prosthesis via more natural physiological pathways. This means that the patient can try to activate muscles that would normally be used for a movement, and because the nerves supplying these muscles have been rerouted and usable for the prosthesis, the patient feels a more intuitive control over the prosthesis, rather than using muscles normally unrelated to the intended movement. This results in faster and more precise control of the prosthesis (9).

Another issue with the use of myoelectric prostheses is that detection of EMG signals can be challenging and unreliable. This is due to anatomically close muscles whose contraction can cause interference in the signals, or the thickened scar tissue that is commonly found at sites of amputation (2). Naturally, this leads to imprecise and difficult control of the prosthesis. A potential solution to this is the Implantable Myoelectric Sensor (IMES), where electrodes are implanted within the muscles, allowing for considerably more sites to gather information from. Furthermore, due to their close association with specific motor units, interference from other muscles is greatly reduced. They are wireless and are powered by telemetry coils placed on the user. The sensors relay information to an external receiver that then controls motors of the prosthesis. They may be especially effective in prosthesis control when combined with TMR (7).

Peripheral Nerve Interfaces

Moving one level higher up the chain of motor control leads us to the peripheral nerves that supply the muscles of movement. Logically, interfacing with these structures would be a reasonable alternative to using EMG signals, mimicking the way which normal limbs achieve movement. This is the principle behind the peripheral nerve interface. Furthermore, unlike a myoelectric interface, bidirectional information transfer is possible here, which opens up the prospect of somatosensory feedback. The peripheral nerve interface consists of a set of electrodes that are attached in some way to the remnants of the nerves that innervated the muscles of the limb, which, despite amputation, are still functional and follow the same pathways as before. The electrodes detect electroneurographic (ENG) signals from the nerves, which are then relayed to a processor that amplifies and modulates the information, then activates motors that control the movement of the limb (10).

However, there is no one way to go about obtaining information from peripheral nerves. The type of electrode used directly affects its selectivity and activation requirement. The main factor differentiating the electrode types is the degree of invasiveness into the nerve the electrodes are be attached to. The first, and least invasive, is the cuff electrode. As the name implies, this type wraps around the entire circumference of the nerve and makes electrical contact with the epineurium, which is the outer sheath of the nerve. The electrode contacts do not enter the nerve, merely resting on its surface (11). The limitation of this type is that its circumferential nature causes it to have a low surface area, and hence lesser potential for detailed information gathering and selection of specific nerve fascicles. A potential solution to this is to flatten the nerve and apply a flat interface nerve electrode (FINE). This method takes advantage of the fact that nerves can be reshaped by constant forces on them over periods of time, and uses this to expand the surface area available and access more fascicles without increasing the invasiveness of the electrode (12).

Other peripheral nerve electrode types, such as Longitudinal Intrafascicular Electrodes (LIFEs), are more invasive, with information being gathered from inside the nerve itself. To be specific, these electrodes are in contact with the interior of the nerve fascicles themselves. This increases the selectivity of the signals detected and reduces interference from other fascicles that may not transmit information that is useful for prosthesis control. The drawback of this is the danger of damaging the nerve during the implantation, which only increases with the invasiveness of the electrode (13). Due to its function as a nerve sheath, the epineurium is naturally insulating, meaning electrical signals are significantly harder to detect when the electrodes are outside the nerve rather than inside. For similar reasons, intrafascicular electrodes must penetrate the perineurium (which surrounds individual fascicles) as well. Due to the reduced resistance to electrical conduction within the fascicles as well as the increased number of electrode sites, even more information can be obtained compared to non-invasive (11). However, attempts to obtain more specific information have been made. An example of this is the sieve electrode, which is able to obtain information from each individual axon within a given nerve. However, the method of implantation is extremely invasive. It involves severing the entirety of the nerve, placing the sieve electrode between the cut ends and then letting the nerve regenerate with the electrode within it. The axons regenerate between the openings in the electrode, allowing discrete information to be obtained from each of them (14).

Cortical Interfaces

The final interface to be discussed is the cortical interface. In this modality, electrical signals for prosthesis control are obtained directly from the motor cortex of the brain itself, rather than peripheral tissues such as muscles or nerves. The advantage of using the central nervous system is that it provides an alternative site of information acquisition in patients with conditions that result in them being unable to send signals to said peripheral structures. Devices that can be controlled using cortical interfaces would be more useful for rehabilitation and quality-of-life improvement of patients affected by these conditions (15).

Cortical interfaces have sub-modalities of varying invasiveness. In most clinical scenarios where brain activity needs to be monitored, electroencephalographic (EEG) information, obtained via cutaneous electrodes, is used. However, while this method is noninvasive, the information gathered is of too low resolution to allow precise control of a prosthetic limb as the electrodes are excessively distant from the brain. A more invasive modality is electrocorticographic (ECoG) information, where the information is obtained from platinum electrodes placed on the surface of the brain cortex. ECoG signals are currently the most widely used data acquisition modality for cortical interfaces. Lastly the most invasive modality is the low-field potential (LFP). Data is obtained via microelectrodes that pierce the cortex. These latter two modalities can be used in parallel as the signals they detect may encode different information about movements (16).

Motor control of the body arises from the part of the brain known as the motor cortex, which is located on the pre-central gyrus. Different parts of this cortex give signals to different parts of the body, and a relatively large cortical area is dedicated to control of the upper limb, the hand in particular, which is representative of the high dexterity of this appendage. The concept of these different cortical areas controlling different body parts can be used to develop a "map" (often represented as a person, the motor homunculus) for cortical brain-machine interface. This would mean that electrodes placed at a point that has been determined to control elbow movements, such as flexion and extension, would pick up signals when the patients wanted to perform said motion. These signals can then be processed into electronic commands for a prosthetic limb. This has led to the development of ECoG grids, which can be chronically implanted into the patient for years and overlaid onto the parts of their motor cortex that controls the limb to be replaced (17). However, the primary issue with the use of brain-machine interfaces is that electrode implantation causes reactive gliosis at the site. Gliosis is a form of tissue scarring where hyperplasia and hypertrophy of glial cells of the brain occur. This process is mediated by microglial cells, which have an immune-like function in the brain, and attach to the surface of the electrode after implantation in an attempt to destroy it. The result of this gliosis is the formation of a glial scar around the contact surface of the implanted electrodes, which interferes with and ultimately prevents the recording of cortical signals. In fact, although there is variation amongst patients, it has been found that around half of chronically implanted cortical electrodes are incapable of recording after several months, which results in reduction in the resolution of the information gathered and reduced control of the prosthesis over time (18).

Nonetheless, there are definite advantages associated with the use of cortical interfaces to control prostheses. Aside from the fact that it is the only type usable by those patients who cannot send peripheral signals, using cortical interfaces to control prostheses allows the patient to perform movements using the limb by merely "thinking" of doing so. This reduces the need for extensive training as the patients do not need to learn new and often unintuitive control schemes. Indeed, studies have shown that patients implanted with these interfaces were able to achieve reasonable control over a prosthesis with only an hour of practice, and the only aspect of control that had to be significantly changed were the algorithms that translated the patient's ECoG signals into movement of the limb (19).

Somatosensory Feedback Systems

Somatosensory feedback signaling is necessary for the precise and coordinated movements observed in physiological limbs. These signals comprise large amounts of information, including the sensations of touch and pressure, the spatial position of limbs and joints, and temperature of the environment of the limb. As a whole, somatosensation of any part of the body allows the person to "embody" the appendage, and consider it part of their "self" (20).

As it currently stands, robotic limbs have almost-biomimetic movement and degrees of freedom; the issue is that patients are unable to utilize this to perform tasks requiring dexterity and precision (21). To achieve this, the prosthetic limb should have some form of somatosensory feedback, which would result in a significant increase in the user's ability to perform complex non-preprogrammed motions (22). This is because the brain will be able to use the somatosensory feedback to modulate the signals it sends to move the prosthesis in a way that is far more intuitive and natural than the user having to observe their own movement and having to consciously decide when to interrupt or change the action. However, this retrograde transfer of information has proven to be considerably more challenging than in the usual human-to-prosthesis direction (23).

Much like achieving motor control of a prosthesis, there are multiple methods to deliver somatosensory information from prosthesis to body. In this situation communication must be with the nervous system as information transfer in myoelectric interfaces is unidirectional while peripheral nerves contain both afferent sensory axons and efferent motor axons, allowing for bidirectional information transfer. The peripheral sensory interface type can potentially be used in conjunction with osseointegration of the prosthetic limb house, which can provide a site for a permanent bidirectional interface between the user and the prosthesis (4). Lastly, brain-machine interfaces can also be used to transmit somatosensory information. However, while cortical interfaces for motor control made use of the motor cortex, such an interface for somatosensation must use the sensory cortex, which is located on the post-central gyrus of the brain.

As before with peripheral nerve interfaces, there are varying sub-types of electrodes, with their selectivity in accessing particular nerve fascicles increasing with their degree of invasiveness. However, there are ways to increase the selectivity of axon activation while minimizing invasiveness. For example, due to the decay of the electrical signal sent from a non-penetrative spiral electrode and the particular slew rate for the activation of a given axon, using electrical pulses of differing waveforms will allow axon types to be activated selectively depending on their size, myelination and distance from the electrode (24). In normal nerve physiology, the frequency of action potentials indicates the intensity of the stimuli being sensed, and this interface mimics that by modulating the frequency of the electrical signals delivered with the intensity detected. These methods have been shown to be able to elicit significantly localised sensations of touch of the phantom limb in amputees, allowing for improved motor control of prosthetic limbs (25).

Alternatively, if the somatosensory interface were to be of the cortical type, it would have to lie on the primary sensory cortex. This part of the cortex is further divided into four areas called Brodmann's areas, to which neurons for particular sensations are localised. For example, one area is responsible for proprioception while another deals with pressure and light touch. Due to the highly precise and often complex nature of movements and sensations of the upper limb (particularly the hand), there is a considerable surface area of the sensory cortex devoted to processing of stimuli from this limb. With this knowledge, and the concept of the sensory homunculus (which is essentially the same idea as the motor homunculus described earlier), it would be possible to elicit localised sensations of various stimuli to parts of the limb that is to be replaced. This would be accomplished by using intracortical microstimulation (ICMS) to selectively activate neurons that are involved in the sensation of the stimuli to be delivered (26). As with peripheral nerve stimulation, the frequency of these electrical pulses indicate the intensity of the stimuli detected. However, in the cortical interface, modulation of the amplitude of the ICMS will also increase the intensity of the stimuli, and this is because a stronger signal will activate a larger number of neurons in proximity to the electrode (27).

The main difficulty in implementing cortical somatosensory interfaces is cortical plasticity. Due to cessation of afferent input from the lost limb, parts of the brain that normally process information from that limb begin doing so for other parts of the body instead. This means that electrical stimuli delivered to create sensations in part of the prosthesis may cause these sensations to be perceived as coming from elsewhere. Nevertheless, it has been shown that despite some changes in the organisation of the sensory cortex after limb loss, stimuli delivered to the appropriate areas will still cause sensations in the phantom limb (27).

Conclusion

For much of history, loss of a limb has been seen as a significant disability. Loss of legs led to negligible mobility and independence while loss of arms presented an incredible challenge to basic function. With the development of bionic prostheses, society stands at a point where the loss of a limb may soon become a far less debilitating incident, where much of the functionality of a normal limb can be restored.

Looking to the future, it is likely that improvements in both the interfaces and the mechanical components of prostheses will lead to increasingly biomimetic functioning of prosthetic limbs. However, it is increasingly possible that bionic limbs may not just replicate the normal functions of a limb, but augment it; functions that are not capable of being performed by normal limbs could be performed by bionic limbs: for example, the ability to lift heavier weights or manipulate the limb in novel manners may be introduced. Examples of such novel non-biomimetic functions can even be seen in prostheses today: users of the Bebionic myoelectric arm are able to rotate their wrists a complete 360° (28), and due to the materials used in modern prostheses, most allow users to grasp items such as hot or sharp objects that would normally injure a biological hand. Given that much of the funding for research in this field comes from the militaries of various countries, the potential for limb augmentation grows year by year.

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