Recent advances in bioelectric prostheses

Paul F. Pasquina, MD
 Briana N. Perry, BA
 Matthew E. Miller, MD
 Geoffrey S.F. Ling, MD, PhD
 Jack W. Tsao, MD, DPhil

Summary

Worldwide prevalence of amputation has created an increasing demand for improved upper and lower extremity prostheses. Current prosthetics are often uncomfortable and difficult to control and provide limited functional restoration. Moreover, the inability to normalize anthropomorphic biomechanics with a prosthesis increases one's risk of developing long-term health risks such as arthritis, skin breakdown, and pain. Recent advances in bionic prosthetic development hold great promise for rehabilitation and improving quality of life with limb loss. This brief review discusses the current state of advanced prostheses, the integration of robotics in the care of individuals with major limb amputation, and some innovative surgical techniques that are being explored for clinical feasibility.

In 2005, approximately 1.6 million persons with limb loss were living in the United States, and it is estimated that the number will more than double by 2050.¹ Major causes include diabetes mellitus, vascular disease, trauma, and bone/joint malignancy. As of April 2014, 1,645 US military service members have sustained a major limb amputation as a result of combat injury—many sustaining loss of more than one limb (J.C. Shero, Director of the Department of Defense and Veterans Affairs Extremity Trauma and Amputation Center of Excellence, personal communication, April 2014). Within developing countries, approximately 0.5% of the population is estimated to have physical disabilities requiring use of prosthetics or orthotics.² The effect on global health and quality of

Department of Physical Medicine & Rehabilitation (PFP), Center for Rehabilitation Sciences Research (PFP, JWT), and Department of Neurology (GSFL, JWT), Uniformed Services University of the Health Sciences, Bethesda, MD; Walter Reed National Military Medical Center (PFP, BNP, MEM, JWT), Bethesda, MD; and US Navy Bureau of Medicine and Surgery (JWT), Falls Church, VA.

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Correspondence to: Jack.tsao@usuhs.edu

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life for individuals aging with disability is important to consider and highlights the need for improved prosthetic development.

Upper extremity prostheses

There are 3 types of functional arm prostheses: body-powered, motorized, and hybrid (composed of body-powered and motorized). Body-powered prostheses typically consist of a cable system that connects a terminal device to a shoulder harness so that when the cable is stretched by arm or shoulder motion the prosthetic hand or hook opens or closes. This system allows for control of only one degree of freedom (of movement) at a time. Comparatively, the movements of a motorized prosthesis are driven by a battery-powered electronic motor. Myoelectric prostheses and centrally controlled prostheses are subtypes of motorized prostheses that differ based on their control signals.

Myoelectric prostheses harness the EMG signals of residual limb muscles to trigger the function of a robotic prosthetic arm or hand. There are a variety of sophisticated, commercially available myoelectric prostheses that use surface EMG signals (table). While these devices have greatly improved over the past decade, they are still limited by their number of controllable degrees of freedom, intuitiveness, and reliability. Additional restrictions include weight, limited battery life, and the user’s inability to control multiple degrees of freedom simultaneously and consistently. Because the myoelectric signals are captured through surface electrodes on the skin, poor socket fit, excessive socket rotation, and residual limb sweating can frequently alter performance. In addition, because the myoelectric signals are generated from residual limb muscles to perform actions they were not intended for, the use of these devices is not intuitive (e.g., contracting a biceps muscle to trigger prosthetic hand closing). This is most challenging for individuals with amputations at the transhumeral or shoulder disarticulation level. Therefore, despite numerous advances in the field, rates of user abandonment for upper limb prosthetic systems remain high.³

Centrally controlled prostheses operate via cortical inputs that allow for the operation of a prosthetic arm. This type of motorized prosthesis falls into the category of brain-computer interfaces. A brain-computer interface is an alternative method to record and interpret the communication between the CNS and the pathways of the peripheral nervous system through both invasive and noninvasive techniques.⁴ Past studies have used the brain-computer interface with primates in a virtual environment to control specific actions from nerve feedback,

Table A sampling of myoelectric upper extremity prostheses that are commercially available	
Model	Company
Michelangelo Hand	ArmDynamics
SmartHand	BioRobotics
Digital Twin Hand	Ottobock Healthcare
Dynamic Mode Control	Ottobock Healthcare
MyoHand VariPlus Speed	Ottobock Healthcare
SensorHand Speed	Ottobock Healthcare
i-Limb Ultra	Touch Bionics

Figure 1 Modular Prosthetic Limb

Images courtesy of The Johns Hopkins University Applied Physics Laboratory and the Defense Advanced Research Projects Agency.

allowing the primates to control a bench-mounted neuroprosthetic device.^{5,6} Other research has provided an accurate mapping between the onset of neuron stimulation and an expressed motion through direct cortical stimulation.⁷ Further analysis of this brain-computer interface has led to breakthrough research in which an individual with tetraplegia was given capability to manipulate bench-top motorized prosthetic movement.⁸

For either type of motorized prosthesis, recording and processing signals from a greater number of residual muscles through pattern recognition may also improve prosthetic function. Pattern recognition relies on advanced algorithms to decode multiple simultaneous EMG signals captured through an array of surface electrodes placed on the residual limb in order to control intended prosthetic action. Trials are currently under way to utilize pattern recognition to control more advanced robotic arms, such as the Modular Prosthetic Limb (MPL; figure 1) and DEKA arm, both of which were developed through the Defense Advanced Research Project Agency Revolutionizing Prosthetics program. The MPL provides up to 26 degrees of freedom of volitional control through the use of 17 actuators that capture EMG signals.⁹ The DEKA arm operates via neural signals from a 96-channel microelectrode array implanted in the motor cortex, and persons with tetraplegia have used it to accomplish reach and grasp motions.¹⁰ These 2 arms are not yet commercially available and have planned improvements regarding size and weight reduction. Furthermore, in preliminary studies the DEKA arm has been shown to produce reach and grasp actions that are not as fast or as accurate as those of an able-bodied person.¹⁰ However, while supporting the challenges inherent to EMG control, both prostheses provide excellent platforms to test novel user-interface control strategies, including foot and joystick controls as well as brain-computer interfaces.

A novel surgical intervention to improve myoelectric prosthetic control is targeted muscle reinnervation (TMR). This procedure involves reconnecting transected nerves to remaining muscles within the residual limb or chest. By doing so, each newly innervated muscle is able to generate a unique myoelectric signal, thereby increasing the overall number of sites of control and enhancing prosthetic function.¹¹ Furthermore, because these reinnervated muscles respond to neural input originally intended for hand or wrist actions, the new sites of control are generally more intuitive for the user. For example, if the long head of the biceps retains its innervation from the musculocutaneous nerve and is used to trigger prosthetic elbow flexion while the short head of the biceps is reinnervated by the median nerve and is then used to trigger hand closure, the user has doubled the sites of control, and both movements are easier to perform. Although patients who have had TMR surgery are able to control a greater number of degrees of freedom more intuitively, they still experience similar challenges as traditional myoelectric systems, including motion-selection time delays and lack of sensory feedback.¹¹ These patients require a greater array of surface electrodes, which have limitations related to socket fit and skin sweating.

Direct skeletal attachment of a prosthesis (e.g., osseointegration) may offer a solution to the challenges of socket interfaces.

Because of the limitations inherent in using surface electrodes and the technical challenges of using brain-machine interface techniques, the development of implantable electrodes holds great promise in controlling myoelectric prostheses. Currently, a clinical feasibility trial is being conducted with implanted myoelectric sensors (IMESs).¹² These sensors are approximately the size of a long grain of rice and are able to record and transmit EMG signals outside the body wirelessly through a magnetic coil embedded within the prosthetic socket (figure 2). The system offers simultaneous control of multiple myoelectric sites, thereby allowing combined control of multiple degrees of freedom. The system has a higher (i.e., better) signal-to-noise ratio and greater signal reliability and allows for capture of myoelectric signals from deeper muscles, enhancing the intuitive control of the prosthesis. Outstanding technological issues include the desire to reduce power consumption and enhance the telemetry to deeper implants.¹³

Research is also being conducted on the haptic feedback, or the natural sensory feedback, provided to the user from these prosthetic devices, which would allow the user to feel what the prosthetic hand is feeling (e.g., force, texture, temperature). Currently, no feedback is given to the user directly and instead feedback must be embedded within the prosthesis by means of artificial intelligence or the control of low-level motion decisions by the prosthetic device. For example, the Ottobock SensorHand Speed hand (Ottobock Healthcare) can sense an object slipping and tighten its grasp in response. However, development is under way to provide haptic feedback directly to the prosthetic user. One method utilizes vibrotactile and pressure actuators built within the prosthetic socket.⁹ Another potential feedback source is C2 tactors, which place pressure on reinnervated skin corresponding to the degree of pressure on the prosthesis, ultimately allowing the user to understand the force felt by the prosthetic hand.¹⁴ In addition, current studies using the Case Western Reserve University spiral neural cuff electrode, the Utah slant electrode, and transverse intrafascicular multichannel electrodes are exploring the use of peripheral nerve interfaces to provide sensory information to individuals with upper

Figure 2 Photograph of implanted myoelectric sensor (IMES) components in 3 assembly states

(Top) IMES silicon chip. (Middle) Sectioned IMES capsule containing IMES subassembly. (Bottom) Completed IMES implant. Shown next to 1 mm scale. © 2009 IEEE. Reprinted, with permission, from Weir RF, Tryok PR, DeMichele GA, Kerns DA, Schorsch JF, Maas H. Implantable myoelectric sensors (IMESs) for intramuscular electromyogram recording. *IEEE Trans Biomed Eng* 2009;56(1):159-171.

Figure 3 Osseointegration in a patient with transfemoral amputation

Images courtesy of St.-Jean C, Fish N. Osseointegration: examining the pros and cons. *inMotion* 2011;21(5):46-47.

extremity amputation and to augment their control of neuroprostheses.¹⁵⁻¹⁸ Once developed, these systems have the potential to enhance the prosthetic user experience.

Lower limb prostheses

Over the past decade there have been a number of advances in lower limb prosthetics, including improvements in socket and individual component (e.g., foot, ankle, knee, hip) design. Modern sockets are currently fabricated to provide “total contact,” distributing mechanical forces more evenly through the residual limb, in contrast to previous sockets that provided focal areas of weight bearing. In addition, more sophisticated polymers and carbon fibers are being used to generate sockets that are lighter weight and more durable and allow combinations of rigidity and flexibility to optimize performance. Similarly, novel liners provide thinner and more comfortable fit and can even enhance suspension (e.g., Seal-In liner). Despite these improvements, socket fit, performance, and comfort continue to present major challenges, as many individuals have chronic problems with skin breakdown, infection, and pain. Direct skeletal attachment of a prosthesis (e.g., osseointegration) may offer a solution to the challenges of socket interfaces (figure 3). Complications from this technique include an increased risk of infection at the site of skin penetration of the metal abutment. While this technique has been utilized successfully in several European centers, it is currently not approved by the US Food and Drug Association for use within the United States.

An improved understanding of the biomechanics of locomotion has contributed to enhanced lower limb prosthetic component design. Dynamic response feet utilize advanced metals and polymers to allow dampening of ground reaction forces and return of energy through the recoiling effects of the materials that are deformed. The shape and configuration of these feet are influenced by the presence or absence of rotational components, the presence or absence of bumper stops for plantar and dorsiflexion, and the design of forefoot or heel keel, which is the part of the prosthesis that deforms or recoils in response to the amount of weight bearing and ground reactive force. These features may provide greater or lesser ankle or foot motion to enhance participation in various sports and recreational activities.

Similarly, many advances have occurred in the design and function of commercially available prosthetic knees. They are composed of 2 major categories: passive knees and powered knees. Passive knees can be further divided into the 2 categories of mechanical knees and microprocessor-controlled variable-dampening knees. Mechanical knees include both friction

Figure 4 Lower limb prostheses

(A) The Genium. Image courtesy of Ottobock. All rights reserved. (B) The POWER KNEE. Image courtesy of Össur, Inc.

knees and hydraulic stance and swing-control knees. The advantage of mechanical knees is that they are lightweight and low maintenance, but they are typically limited to single-speed ambulation and level-ground walking or may be sports and recreation specific, such as knees for running, cycling, or skiing. Comparatively, microprocessor-controlled knees utilize computer chips to interpret signals from a gyroscope and an accelerometer that are embedded within the leg to provide variable resistance to knee motion, thereby promoting quick adaptation to changing ambulation velocities. They have demonstrated increased efficacy compared to mechanical knees in the areas of cost, safety, energy, and level of activity.¹⁹ The Genium (Ottobock Healthcare) (figure 4A) and Rheo Knee (Ossur, Inc.) are 2 of the most popular commercially available microprocessor-controlled variable-dampening knees.

Newly available “powered” lower limb prostheses incorporate motors and actuators, artificial muscles that produce force and movement within the limb to replace lost muscles and restore more normal gait and function. Powered prosthetic knees have demonstrated greater energy advantage compared to microprocessor knees, particularly with faster walking speeds and with stair and ramp climbing, because of their ability to replace the power lost from amputated muscles. Evidence also supports enhanced symmetry during ambulation, promoting sufficient heel rise and potentially reducing hip hiking and hip torque.^{20,21} Clinical trials are currently under way evaluating the efficacy of 2 commercially available powered lower limb prostheses: POWER KNEE by Ossur (figure 4B) and the BiOM Ankle System. Powered lower limb prostheses share similar limitations to those of upper limbs, including excessive weight, short battery life, and limited user control interface. Strategies to incorporate pattern recognition signals, TMR, and IMESs are currently being tested.²⁰

DISCUSSION

While many advances have occurred in the development of novel prostheses, individuals with limb loss continue to be at higher risk for many long-term health complications, including arthritis, cardiovascular disease, pain syndromes, and reduced quality of life.²¹ Widespread use of advanced prosthetic technologies may decrease some of these risks for future generations. Unfortunately, high manufacturing costs and variable insurance coverage serve as considerable barriers to prosthetic access. These factors are magnified in many developing countries, especially where knowledge and access to prosthetic technologies is not universal. Nevertheless, while much remains to be done with regard to the development, evaluation, and distribution of bioelectric prostheses, the recent technological advances and surgical innovations related to prosthetic design promise to offer greater functional restoration after major limb loss.

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