Prosthetic Advances

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Much of the current prosthetic technology is based on developments that have taken place during or directly following times of war. These developments have evolved and improved over the years, and now there are many more available options to provide a comfortable, cosmetic, and highly functional prosthesis. Even so, problems with fit and function persist. Recent developments have addressed some of the limitations faced by some military amputees. On-board microprocessor-controlled joints are making prosthetic arms and legs more responsive to environmental barriers and easier to control by the user. Advances in surgical techniques will allow more intuitive control and secure attachment to the prosthesis. As surgical techniques progress and permeate into standard practice, more sophisticated powered prosthetic devices will become commonplace, helping to restore neuromuscular loss of function. Prognoses following amputation will certainly rise, factoring into the surgeon's decision to attempt to save a limb versus perform an amputation. (Journal of Surgical Orthopaedic Advances 21(1):58–64, 2012)

Key words: prosthesis, prostheses, prosthetic, amputation, rehabilitation

Introduction

Much of the technology currently used in the field of prosthetics is not exclusively new. Rather, it is a compilation of modern techniques and products built on tried-and-true principles learned from historical advances. Just as "war is the only proper school for surgeons" (Hippocrates), many developments in amputation surgery and prosthetic technology have developed as a result of armed conflict in response to a new population of young, previously healthy and active amputees dissatisfied with their putative limitations. Advances during both times of war and peace have come mostly by way of observation of best practices, partnerships with industries, research and development initiatives, businesses striving for better competing products, and individuals seeking innovation. According to Bowker and Pritham (1):

"The idea for suspending a socket through suction was patented in the United States (US) in 1863, but wasn't utilized frequently in the US until World War II when US military surgeons and engineers noted the success that Germany was having with the suction suspension valve on their veteran amputees. Today, suction is the primary means of socket suspension utilized by the military amputee population. During WWII, Northrop Aviation engineers helped to develop lighter weight and more functional body-powered upper limb prostheses based on aircraft knowledge and materials. Also during this time, the first prosthetic research laboratory was originated and resulted in biomechanics laboratories and work which led to the development of hydraulic knee joints, improved socket designs, and a solid rationale for surgeons to save all practicable limb length to preserve function. In 1970, the German company Otto Bock introduced lightweight, modular endoskeletal components that could easily be aligned. These almost entirely replaced the need for exoskeletal designs. Amputee-prosthetist Ossur Kristinsson developed flexible walled sockets and roll-on gel liners in the 1980's and 1990's, which have led to the current state of the art in socket and interface technology."

In today's landscape of prosthetic technology, many more options and techniques are available than ever

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before. Dynamic response feet constructed predominantly of carbon fiber, urethane, and titanium provide good energy return and ground accommodation (2–9). Microprocessor knees have enabled safer, more versatile, and more efficient ambulation (10–14). Upper extremity devices are rapidly changing to include more degrees of freedom, and becoming more intuitive and responsive, as a direct result of government-funded initiatives (15). Prosthetic feet, knees, hands, and other components are available to suit virtually any specialized need or activity where a standard prosthesis is not appropriate (16). Interface and suspension are slowly improving as manufacturers compete to produce a better product. A myriad of aesthetic options are available, including stunningly realistic high definition silicone restorations, helping with acceptance of body image.

Despite the vast number of products and techniques available for the prosthetist to attempt to restore the loss of limb(s), technological limitations persist. Perhaps the most critical part of the prosthesis is the socket and interface. Patients consistently rate comfort as being more important than either function or cosmesis (17). The most technologically sophisticated prosthesis will not be used if it is not comfortable. The struggle to provide the perfect socket requires patience, perseverance, and acceptance when a realization is met that perfection is never fully attainable. That said, emerging materials and technologies continue to evolve and address the needs of the combat-injured amputee; these advances will gradually migrate to the arena of civilian amputee care in coming years.

Lower extremity prosthetic advances

It is well known that persons with amputation require increased energy expenditure to ambulate compared to age-matched non-amputees, and that the more proximal the level of amputation(s), the higher the increase in energy requirements (18–22). Additionally, in order to successfully ambulate, compensatory gait patterns are necessary but may lead to low back pain, premature degenerative joint disease, and variety of other maladies (23–29). The sound side ankle plantarflexes nearly 20 degrees (30) during late stance and, among the lower extremity joints, is the greatest propellor during over ground gait (31). The iwalk BiOM (Bedford, MA) is the first commercially available foot and ankle to generate power in the form of active plantarflexion during late stance in gait (Fig. 1). Bionic and biomemetic controls acquire information from on-board sensors and send output to an actuator, which in turn moves the ankle as programmed. Preliminary data from a study conducted at the Center for the Intrepid in San Antonio, TX, has found the energy consumption of those unilateral transtibial BiOM wearers comparable to able-bodied controls (32). Whereas traditional prostheses generally restore only the skeletal loss following an amputation, the BiOM succeeds in restoring some motor aspects of neuromuscular loss as well. This technology should continue to improve with better battery technology, more sophisticated algorithms, and as other manufacturers attempt to compete in this market. Powered ankle and knee combinations are the next logical step of development and will follow suit with much of the recent progress made in upper extremity prosthetics. Pattern recognition shows some promise as a highly intuitive control scheme for the lower as well as upper extremity and would enhance the responsiveness of such systems (33).

During level ground-walking, normal gait reveals 15 to 20 degrees of knee flexion during loading response (34). This serves as a shock absorbing mechanism and is one of the key determinants of gait (35,36). Many microprocessor prosthetic knee joints are now designed with a feature called "stance flexion" and allow the user to push freely into the knee joint, allowing it to bend, and later pulling back in the socket to progress over the prosthesis. Few persons with transfemoral amputations, especially those with long, strong residual limbs, utilize this stance flexion feature (37,38), and prefer to power back in the prosthesis, keeping the knee joint locked throughout the entire phase of stance because of the feeling that the knee is giving way. It is highly possible that this contributes to the high prevalence of low-back pain associated with transfemoral amputees (39).

Traditional prosthetic knees are passive in nature and are designed to balance stability with mobility during the gait cycle. Microprocessors have helped to improve the timing of this balance and even anticipate actions such as the stumble recovery feature of the Otto Bock C-leg (Minneapolis, MN). The Ossur Power knee (Aliso Viejo, CA) is the first commercially available knee to

FIGURE 1 The BiOM powered ankle is the first commercially available device to deliver powered plantarflexion. This is thought to improve walking efficiency and lessen compensatory gait deviations. Photo courtesy of iWalk, Bedford, MA.

generate power during the gait cycle and actively assist in powered knee extension when exiting a chair and when ascending slopes and stairs. For flat ground ambulation, it is theorized that so long as stance flexion is utilized, the powered extension may lessen lower back strain and will improve energy efficiency during walking. Initial observations show that more people utilize stance flexion with the power knee than with traditional prosthetic knees. The Power Knee works during swing phase as well to equalize timing. It is not clear whether powered knee extension during swing phase is necessary compared to traditional prosthetic knee mechanics.

Additionally, versatility is somewhat lacking in traditional knee joints. Some knees consistently yield while descending ramps and stairs while others consistently lock out under these conditions. Some knees are dangerously easy to swing forward while others require more deliberance, exertion, and effort. Current waterproof knees are not necessarily optimal for everyday use. When designing a knee that was versatile and durable enough to return some combat injured amputees to duty, the Military Amputee Research Program funded Otto Bock (Minneapolis, MN) to develop the X3 knee. The X3 design requirements were that it be capable of walking on uneven ground, walking backward, carrying heavy loads, running on without adjusting the settings, and submerging in water. As a spin-off of the development, Otto Bock has very recently released less-ruggedized versions, the X2 (Fig. 2) and Genium, to be sold to the civilian sector as well as the military. While not powered technology in the sense that concentric power is being restored to the gait cycle, these knees deserve mention as emerging and promising technology as initial feedback has been outstanding and clinical observations have shown quick adaptation times, more utilization of stance flexion, and increased versatility during different walking patterns and terrain situations.

FIGURE 2 The X2 microprocessor knee (Otto Bock, Minneapolis, MN) has five on-board sensors that help to more intuitively balance the requirements of stability and mobility under various ambulation conditions.

Surgical advances

Osseointegration is an emerging surgical technique for direct skeletal attachment of prostheses which may one day render sockets antiquated and obsolete for many patients. Although the attempted permanent coupling of metallic implants to the skeleton has been in use for decades in the maxillofacial and dental fields, this field has expanded to residual limbs in only the last two decades (40). Typically, a titanium or other alloy device is first inserted into the termimal bone of the residual limb, and then delivered through the skin via attachment of the prosthesis coupling during a second, staged procedure. This results in improved anchorage and responsiveness of prostheses, as well as greater proprioceptive feedback for the patient. Problems such as sweating, skin irritation from liners, volume fluctuations, and socket pain are thus also eliminated. Early results of these techniques are promising, with high rates of patient satisfaction following implantation in transfemoral and transhumeral amputees. Moderate revision and complication rates persist at present, and infection, fracture, and implant loosening remain concerns (41). The implant-skin interface remains the critical, rate-limiting barrier to the further utilization and widespread adoption of these techniques (42–44). No ossoeintegrated device for major extremity amputations is currently FDA-approved for use in the United States; however, three European groups are actively implanting devices in amputees, and one U.S. group is performing animal trials (45).

Until recently, prostheses for proximal upper extremity amputations were limited by the absence of a sufficient number of independent muscle groups to control separate actions of the elbow joint and terminal device, and the fact that the resulting nerve activation-prosthesis response couplings were not intuitive. Myoelectrics, or all prostheses, were therefore often rejected due to the significant neuromuscular retraining required and, even under the best circumstances, the cumbersome, sequential manipulation of each joint or device.

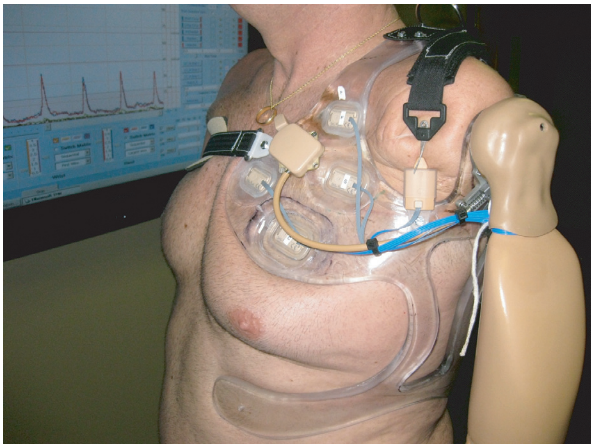

FIGURE 3 Targetted Muscle Reinnervation is a surgical procedure intended to improve the ability for the user to control the movements of the prosthesis. As surgical techniques continue to advance, more sophisticated prosthetic devices will be possible to operate. Photo courtesy of Advanced Arm Dynamics, Redondo Beach, CA.

Targeted muscle reinnervation (TMR) is a novel amputation revision procedure, developed by Kuiken and Dumanian (46–49) wherein motor nerves whose primary target muscle groups have been lost are re-implanted into deliberately dennervated proximal muscles (Fig. 3). This produces an increased number of independent control sites for myoelectric prostheses, which can then be myoelectrically coupled with actions that are intuitively associated with the specific nerve(s). The result is the ability to simultaneously, rather than sequentially, manipulate multiple joints or devices and perform multiple prosthetic actions instinctively. At present, the procedure is most useful for proximal levels such as transhumeral amputations and shoulder disarticulations, and is usually performed as a delayed revision procedure, although acute TMR may prove feasible in the near future.

Advanced pattern recognition (APR) refers to the use of computer algorithms to decipher surface electrode data and subsequently associate specific signal patterns with the appropriate prosthesis response for patients who have undergone TMR (47). For example, the patient repetitively thinks about closing his hand, and the electrode signals associated with this action are then programmed into the myoelectic prosthesis to generate the desired response. This permits even more rapid, intuitive, and fluid device control. Early results of both techniques have been promising.

Additionally, a number of new implantable electrodes have been developed to improve myoelectric device control. These most commonly amplify peripheral nerve signals and thus improve the prosthesis responsiveness via a more reliable neuromuscular unit-prosthesis interface and/or permit the reception of signals from individual muscle groups, allowing more precise prosthesis control (50–56). Prototype electrodes designed for intracranial implantation have also been developed to permit myoelectric prosthesis control directly via signals transmitted from the cortical homunculous (50,57–59).

Upper extremity prosthetic advances

Upper extremity prosthetics devices have made profound advancements in recent years. There have been new surgical advancements in upper extremity amputation techniques and residual limb-prosthesis interfaces and several advancements in upper extremity prosthetic components.

One of the greatest challenges with upper extremity prosthetics has been patient acceptance. Recent studies have found higher replacement and use rates and lower abandonment rates of upper extremity prostheses among Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF) combat-wounded service members compared to those from the Vietnam era (60,61). A higher acceptance rate amongst wounded warriors from OEF/OIF can be attributed to several factors including improved technology for upper extremity prostheses (60), increased rehabilitation and occupational therapy time, and a general cultural acceptance of a blending between man and machine. New terms have risen in modern culture to describe the blend of man and machine such as "cyborg" and "bionic." Although myoelectric prosthesis have been available since the 1960's and early 1970's, most patients fit with upper extremity devices in the civilian world have used body-powered prosthetic devices. With advancements in surgical techniques, new requirements will become commonplace amongst upper extremity components. In the past, myoelectric prostheses would have to be controlled sequentially, i.e. flex elbow-lock elbow, rotate wrist–open hand-close hand. Work is being done to combine these actions into simultaneous control with all actions, or at least multiple actions, taking place at the same time. This increased simultaneous control will allow the upper extremity prosthesis to function faster and more efficiently.

As a result of cooperative of government initiatives and investment, such as the Defense Advanced Research Projects Agency funding, educational research programs, and private industry interests, there have been promising recent advances in upper extremity prosthetics. Recent work includes development of prosthetic arms that have more degrees of freedom than current technology; some experimental prostheses have up to 27 degrees of freedom (15).

Several manufacturers are developing externally powered, microprocessor TMR-compatable elbows (Otto Bock TMR Dynamic Arm, Motion Control Utah TMR, and the Boston TMR) for use with multiple simultaneous

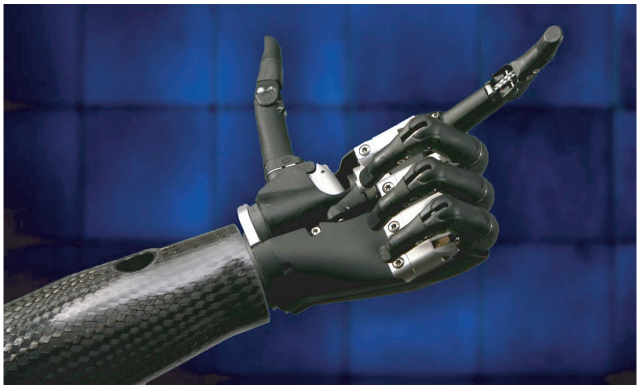

FIGURE 4 Recently, a number of prosthetic hands have been introduced to market, including the iLimb pulse (Touch Bionics, Hiliard, OH), which allow individual finger movement and variation of grip position. Photo courtesy of Advanced Arm Dynamics, Redondo Beach, CA.

inputs, allowing simultaneous control of up to several elbow functions. The microprocessor in the elbow acts like a computer server, processing the myoelectric signal and sending it to the desired powered device (elbow, wrist, or hand). TMR-compatible elbows can process the signals from multiple inputs simultaneously. This allows the user simultaneous control of the components of the prosthesis; wrist, hand, and elbow more closely mimicking the movement of the natural human arm.

Recently, there have been several new multi-articulating prosthetic hands that have come to market. These multi-articulation hands have multiple motors to control different fingers and different hand positions. All of the multi-articulating hands have several pre-programmed hand positions that the user can select from such as: finger point, lateral key pinch, power grasp, mouse click, precision pinch, opposition, and soon-to-be-added wrist flexion and extension. Once the hand position is selected, using myoelectric signals or switches, the user can use myoelectric signals to control the opening and closing of the hand with the particular hand position selected. Multi-articulating hands include: the Michelangelo from Otto Bock, iLimb-Pulse from Touch Bionics (Fig. 4), and BeBionic V2 from Steeper.

Conclusion

Our experience working with hundreds of military amputees from initial injury to years following amputation has provided a wealth of feedback. Advances in surgical and prosthetic technology continue to emerge and, in comparison to past wars, have led to improved outcomes and restored mobility for even the most severely injured wounded warriors. Nonetheless, much "state of the art" technology is not particularly new and many recent developments must move forward past the prototype stage in order to continue true progress. As advanced surgical techniques become more mainstream, continued prosthetic component advancements will also be required. The ultimate goal of prosthetic science is to restore each amputee to his or her pre-morbid level of function; towards this end, much work remains to be done.

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