Chapter 27

THE FUTURE OF ARTIFICIAL LIMBS

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INTRODUCTION

In recent years a remarkable convergence of new science, technology, public awareness, and funding have instigated the development of advanced artificial limbs. For the sake of discussion, research into artificial limbs can be broadly grouped into three different areas: (1) limb interface systems, (2) control systems, and (3) mechatronics. This chapter will document recent developments in these fields, discussing future directions of various innovations as well as areas in need of further research.

LIMB INTERFACE SYSTEMS

Arguably the most important part of any prosthesis is the limb interface system, which must provide both function and comfort. In terms of function, the limb interface system must transfer loads between the prosthesis and the user, and it must allow the user to control the position of the prosthesis. In terms of comfort, the system must allow expedient donning and doffing and be reasonably comfortable while worn, or else the device will not be used.

Sockets and Liners

Advancements have been made to both upper and lower extremity prosthesis sockets and liners, primarily through enhanced materials. Carbon graphite sockets now offer greater durability at a lighter weight. The incorporation of flexible materials within the socket may offer a more adaptable and comfortable socket.

Custom fitting can be enhanced by the use of computer-aided design and computer-aided manufacturing (CADCAM). Computer-aided design has the potential to transform socket fitting from an art to a science. As the understanding of tissue compliance, loading, and force transfer improves, socket-fitting performance and reliability should also improve. In the future, fitting may be completely automated using three-dimensional imagining techniques such as magnetic resonance imagery or computed tomography. Computer-aided manufacturing (CAM) technology also holds promise for improving prostheses because it could reduce fabrication errors and inconsistencies, thereby increasing quality. CAM could also greatly reduce socket fabrication time, allowing amputees the ability to be trained with a custom prosthesis sooner. Finally, CAM could reduce fabrication costs. "Squirt Shape," a technique under development at Northwestern University, is an example of promising CAM research.[1] Unlike many other CAM products that create a socket by removing material from a blank, Squirt Shape places material only where it will be used in the socket. As a result, no material is wasted in the process of extruding the socket from a block, resulting in increased efficiency and decreased waste, and material cost of only $1 per socket. Squirt Shape also uses an automated process to acquire the model of the residual limb, resulting in an accurate and precise model in a short time.

Advances in custom fitting techniques and materials have allowed better suction suspension systems. The Vacuum-Assisted Socket System has been introduced by TEC Interface Systems (St Cloud, Minn) and Otto Bock HealthCare (Minneapolis, Minn). The principle behind this design is to create negative pressure within the socket for suspension, particularly during the swing phase of gait, which may improve residual limb perfusion, reduce limb volume changes, and improve fit and comfort.[2,3] Although objective clinical trials of this technology are lacking, it clearly shows promise for lower limb amputees. Reductions in size and mass will be beneficial. The application for dynamic vacuum suspension systems in upper limb amputees is also being investigated. A simpler means to achieve suction suspension has been introduced by Ossur (Reykjavik, Iceland) in the Iceross Seal-In liner.[4] This system incorporates a membrane lip placed circumferentially around the distal aspect of the liner to cause a "plunger" effect and create negative pressure when moving from stance to the swing phase of gait.

Advances in upper extremity sockets allow self-suspension at the long transradial and wrist disarticulation level and minimize restriction of elbow flexion as well as pronation and supination. Additionally, inventive ways have been developed to incorporate myoelectric sensors and metal connections within silicone and elastomeric liners to improve the consistency of electromyogram (EMG) signal acquisition and improve control of myoelectric prostheses.[5,6]

Artificial Condyles

There are significant advantages to joint disarticulation amputation, including improved suspension from remaining condyles, fixation of the condyles (an important feature in fleshy limbs), rotational stabilization, better weight bearing through the end of the residual limb, and preservation of distal muscle attachment (eg, the adductors in a knee disarticulation). However, joint disarticulations are not commonly performed because when a socket and hinges are placed over the residual limb, the socket is bulky, the limb is functionally too long, cosmesis is poor, and the hinges cause problems with clothing (although some polycentric designs can minimize these effects).

Alternative surgical approaches have been used to preserve the advantages of a joint disarticulation and mitigate the disadvantages. Bone modification can sometimes be done surgically. A midhumeral or midfemoral osteotomy can be done in conjunction with an elbow or knee disarticulation, respectively. This preserves the condyles (for suspension), rotational control, and distal muscle insertions while providing room for a prosthetic joint. Similarly, a humeral angulation osteotomy can sometimes be performed to create a bony element for suspension and rotational control of a transhumeral prosthesis. Unfortunately, these options are rarely available for traumatic amputees due to the inability to perform a disarticulation or lack of bone available for an angulation osteotomy.

Another approach under development is implantation of artificial condyles. Termed "subfascial implant supported attachments," these implants have been inserted in seven patients with transhumeral amputations.[7] This concept presents a viable alternative for individuals whose amputation was caused by trauma, leaving them without sufficiently long bone to undergo other surgical approaches. Initial implants have met with success in five out of the seven subjects, and future refinements of the condyle geometry should provide improved success.

Osseointegration

All the systems described above rely on some type of socket interface. The inherent problem with socket interfaces is that soft tissues are between the load-bearing skeletal structures and the rigid socket systems. These soft tissues are very compliant and thus not efficient in transferring loads. Soft tissues are ill suited for localized high pressure and load bearing, which generally leads to some level of discomfort and frequently causes skin breakdown. Finally, socket systems encase the residual limb, retaining heat and moisture and providing an environment conducive to bacterial growth.

An appealing alternative is the concept of directly attaching prostheses to the skeletal structure, called "osseointegration." Direct skeletal attachment could alleviate the inherent problems of sockets and provide a very efficient mechanical interface for a prosthesis. The first successful model for osseointegration was the dental implant method developed by Swedish bioengineer Per-Ingvar Brånemark. Today, the integration of titanium dental implants is used worldwide. Dr Brånemark's laboratory also performed the first successful osseointegration procedure for artificial limbs, with direct skeletal attachment of prostheses in amputees with short transfemoral amputations.[8] Osseointegration has now been performed in many levels of both upper and lower limb amputations. Clinical trials are ongoing in Sweden, England, Australia, Germany, and Spain, and animal studies are being performed in the United States.

Osseointegration surgery is performed in two stages. First, a metallic fixture is inserted into the medullary cavity of the bone, and the skin is closed over the fixture. Bony ingrowth occurs around the fixture over 3 to 6 months. A pin-line "abutment" is placed into the fixture during the second surgery. An opening through the skin allows the abutment to protrude and serve as the interface for the prosthetic device. A progressive weight-bearing schedule is started soon after surgery. The benefits reported include a secure and rigid attachment that allows excellent mechanical control. Osseointegration systems eliminate the problems with prosthesis sockets described above, providing greater comfort. Additionally, recipients report improved sensory feedback from their directly skeletally attached limb. "Osseoperception"and pro prioception are improved because stiffness between the residual limb and the prosthesis is greatly increased, giving more accurate sensing of the endpoint of the prosthesis. A number of technical challenges remain to be solved before widespread acceptance and use can be expected. The fairly high incidence of infection at the percutaneous interface is of significant concern. Bone resorption, osteomyelitis, and abutment failures are additional complications. Although this procedure is not being performed in the United States because of the relatively high complication rate,[9] the potential benefits are enormous and have inspired ongoing basic science research.

CONTROL SYSTEMS

The lack of control in upper limb prostheses is a severely limiting factor for function, especially for high-level amputees in whom disability is greatest. Current devices use primarily shoulder motion transmitted through Bowden cables or myoelectric control. Body-powered systems allow control of only one degree of freedom at a time with shoulder motion. Myoelectric prostheses also allow operation of only one joint at a time. Myoelectric prostheses are intuitive for transradial amputees to use because hand flexion and extension muscles are present to operate the motorized hand. With higher levels of amputation, however, control is less intuitive because proximal muscles are now used to control distal arm functions. With both body-powered and myoelectric systems the hand, wrist, and elbow must be controlled sequentially, which is cumbersome and slow. Body-powered and myoelectric control can be combined in a hybrid approach that allows simultaneous operation of two joints, although the cognitive burden is high. Finally, existing prostheses provide very little sensory feedback. Body-powered devices give some sensory feedback because the user can feel how hard they are pulling the cable, but no current device provides touch feedback or sensation during object interaction.

The control of lower limb prostheses is also an important issue. Although significant dexterity and multiple degrees of freedom are not required, as with the upper limb, excellent control is required for maximal mobility and safety. Once again, the higher the amputation level, the greater the challenge and need. Significant advances have been made in recent years with computerized knee systems that attempt to predict the intent of the user and adapt to different gait patterns. These systems acquire information only from sensors in the prosthesis, however, and so must rely on other control sources, such as push buttons or key fobs, to allow the user to switch gait modes.

Neural–Machine Interfaces

To address all the above problems, a neural–machine interface that can provide motor commands to operate the prosthesis and serve as a conduit to provide sensory feedback is needed. Three types of neural interfaces are currently being investigated: (1) brain–machine interfaces, (2) peripheral nerve interfaces, and (3) targeted reinnervation. Most limb control signals originate in the brain. As a result, it seems intuitive to tap directly into the source of this information (Figure 27-1), rather than capture it en route (peripheral nerve interfaces) or translate by-products of its endpoint (myoelectric control and targeted reinnervation). A recent increase of encouraging work in this field, termed "brain–machine interfaces," involves individuals with spinal cord injury who are able to control a pointer on a computer screen.[10–12]

Two roadblocks must be overcome before this technology can be considered for prosthetic use. The first involves the complexity of the brain's information structure, and our ignorance of how it works. Although understanding of the brain has grown exponentially in recent decades, very little is understood, from a neuron-to-neuron basis, about how the brain transmits control signals to execute complex movements. Debate remains over the mechanisms involved (eg, force control, position control, synergies). These concepts must be much better understood to bridge the gap between simple control of a cursor and intuitive control of complex trajectories. The second roadblock involves physical connection of the sensor to the brain. Infection around implanted sensors is still a concern, as is heat dissipation for wireless systems. Fixation of sensors to a finite neuron for a long period of time is also difficult. These roadblocks are substantial, but a great deal of basic science research is currently devoted to surmounting them. Brain–machine interfaces might not be used in prostheses for some time, but they are likely to be adopted much earlier for patients with spinal cord injuries.

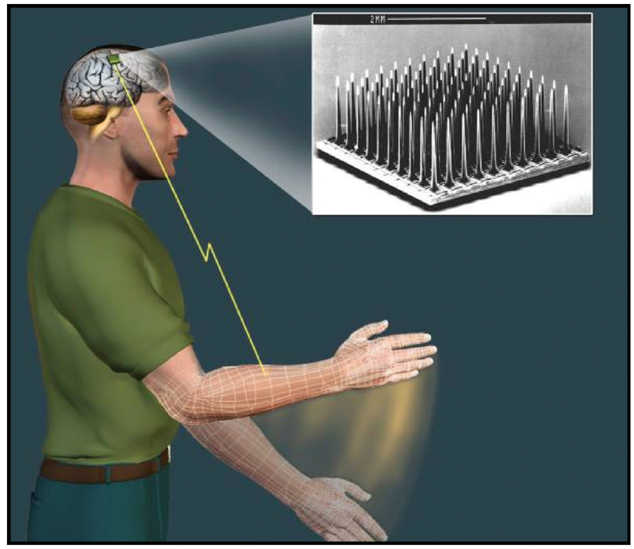

Figure 27-1. The University of Utah's cortical array (inset) records activity from individual neurons in the brain and transmits the signals to a processor outside of the brain. These signals may be used to stimulate muscles of a paralyzed limb, or to control a prosthesis if the limb is missing.
Drawing: Courtesy of John Hopkins University Applied Physics Laboratory and the University of Utah.

In peripheral nerve interfaces, electrodes are directly connected to the residual nerves of the amputee, and the electric signal from the nerve is used to control the artificial limb[13–16] (Figure 27-2). Although this concept offers the potential for improved control, it has several inherent problems such as the fragility of nervous tissue and permanence of electrode array fixation.[17] In addition, the neuroelectric signal is very small, difficult to record, and difficult to separate from EMGs of the surrounding muscle.[18] Additional challenges arise in transmitting signals from the nerve to an external device, which requires either persistent percutaneous

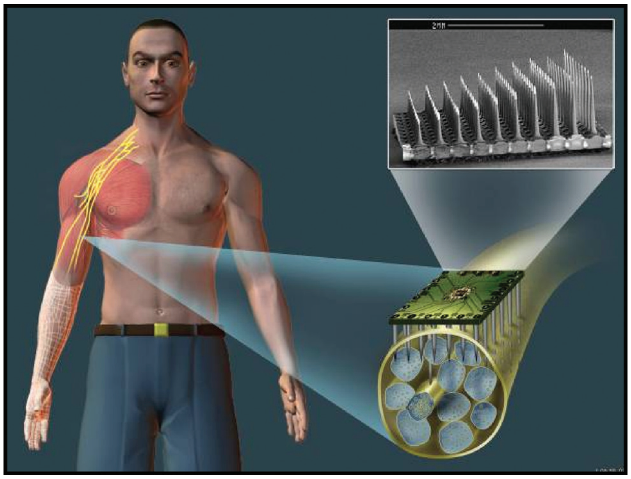

Figure 27-2. The Utah slant array (inset) records activity from individual nerve fascicles of a peripheral nerve. It is implanted into the muscle adjacent to the nerves, as shown in the image in the lower right quadrant of the figure. The slanted tips ensure that nerve fascicles at different depths of the nerves are probed. These signals may then be transmitted to a controller, which in turn controls a prosthesis.
Drawing: Courtesy of John Hopkins University Applied Physics Laboratory and the University of Utah.

wires (which tend to become infected) or complex transmitter–receiver systems. Finally, the durability of the implanted hardware is a critical issue. Prosthetic control systems must function for decades, and implanted neuroelectric control systems may require surgery to repair. At this time several laboratories are making progress toward solving these problems. As a result, peripheral nerve interfaces may one day be widely used, allowing intuitive, finely tuned control.

Targeted muscle reinnervation (TMR) is a new technique that improves the function of myoelectric upper limb prostheses by creating new myosites[19,20] (Figure 27-3). TMR transfers residual nerves from an amputated limb onto alternative muscle groups that are not biomechanically functional due to the amputation. The target muscles are denervated prior to the nerve transfer. The reinnervated muscle then serves as a biological amplifier of the amputated nerve motor commands.[14] TMR thus provides physiologically appropriate surface EMG control signals that are related to functions in the lost arm. TMR with multiple nerve transfers provides simultaneous, intuitive control of multiple degrees of freedom via the motoneuron activity originally associated with the amputated muscles. Great success has been achieved in clinical practice for myoelectric prosthesis control.

Using simple myoelectric control paradigms based on amplitude measurement of the EMG signal de-

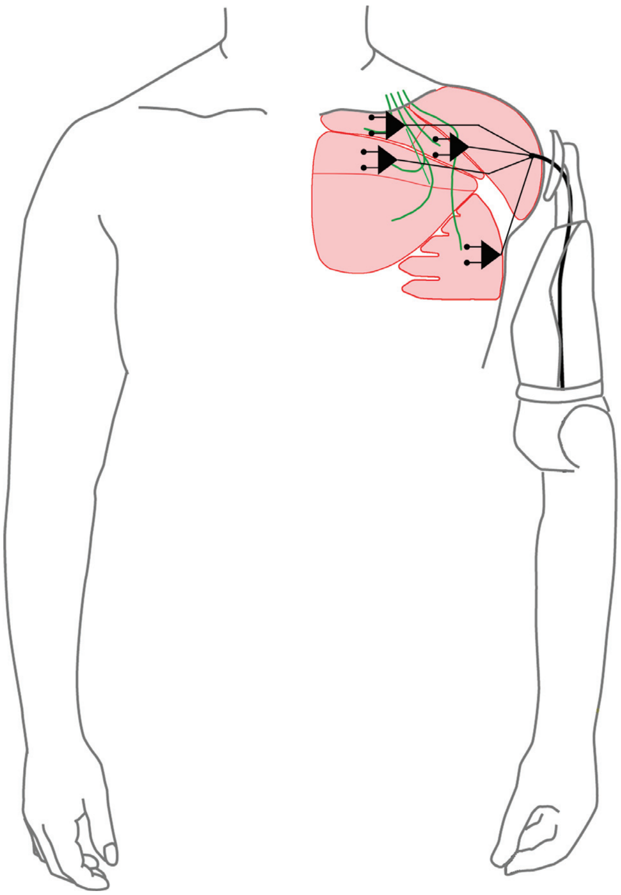

Figure 27-3. Targeted muscle reinnervation reroutes nerves to remaining, nonfunctional muscles. Instead of using artificial implantable sensors, this technique allows the muscles themselves to act as biological amplifiers. Conventional surface electrodes may then be used to sense these new control signals. Signals from these electrodes are transmitted to a microcontroller, which controls the prosthesis.

veloped from each discrete target muscle region, the first four successful TMR patients have demonstrated the ability, for the first time, to control two degrees of freedom simultaneously using only EMG signals. Functional task performance has been evaluated using the box and block test and clothespin test. The subjects have shown a 2.5- to 7-fold increase in speed for task completion. Subjectively, they have reported significantly easier and more natural control of their prostheses.[20–23]

More recent research combines TMR with advanced signal processing techniques to further improve the control of artificial arms. Using pattern recognition classification algorithms, control of advanced prosthetic arms has been demonstrated, including the operation of powered elbows, two-function wrists, and multifunction hands. Targeted reinnervation can also provide physiologically appropriate cutaneous sensation feedback. The afferent fibers in the residual nerves can be directed to reinnervate different residual limb skin, for example, the chest skin of a shoulder disarticulation patient. When this reinnervated skin is touched, it feels like the missing hand is being touched. Studies[23–25] show that the patient can feel very light touch, graded pressure, heat, cold, sharp and dull sensations, and pain—all as if it were in the missing hand.

Current research is being performed to integrate sensors in the artificial hand and tactors (devices that appropriately stimulate the reinnervated skin) into advanced limb systems to provide patients with useful sensory feedback. Broader clinical trials are in progress with current arm systems. Laboratory trials with advanced arm systems are also in progress, and clinical trials with advanced arm systems are planned for the near future. Targeted reinnervation with the potential to improve the function of lower limb prostheses is in the very early stages of development.

Artificial Intelligence

Humans adjust their grasp or gait based on many low-level, unconscious control decisions. If a glass is about to slip, people instinctively tighten their grasp; likewise, as water is poured into a cup, the hand reflexively tightens the grasp. When people start to walk faster, their muscles fire more strongly to prevent the leg from jerking to a stop. This same type of low-level control, termed "artificial intelligence," is even more beneficial in the field of prosthetics, where there is a paucity of control channels. With so few ways to control a prosthesis, it would be ideal for the user to direct only the highest level of control, allowing the prosthesis to provide lower level decisions. Several implementations of this concept have been introduced into prostheses. Examples include the following:

- the Otto Bock SensorHand Speed hand (Otto Bock Healthcare), which senses when an object is about to slip and tightens its grasp;
- the Otto Bock C-Leg (Otto Bock Healthcare), which changes knee resistance depending on the activity required as determined by the prosthesis; and
- the Ossur RHEO KNEE (Ossur, Aliso Viejo, California), which continuously adapts to provide better low-level control of the prosthetic knee throughout the entire life span of the prosthesis.

Future artificial intelligence technology may play a crucial role in orchestrating the control of prosthetic hands with multiple actuated fingers, the interaction of powered lower limb prostheses with the environment to provide proper dynamics, the low-level coordination of prostheses for subjects with bilateral amputation, and many other areas of control.

MECHATRONICS

Powered prostheses consist of three general components: (1) a power source, (2) an actuator and transmission system, and (3) some form of feedback. These components largely parallel the human body. The human arm has two sources of power: (1) the complex network of energy in the form of sugars and fats, and (2) tendons (often forgotten), which absorb and transmit energy during various phases of activities. The actuator in the human arm is muscle, which generates an incredible amount of force but contracts only a minute amount. To move the arm great distances, a transmission is needed, which is found in the bones and muscle insertions. Arm bones and muscle act as lever arms to convert large forces and small movements into smaller forces and larger movements. Finally, the feedback system consists of various layers of sensors and neurons with complex decisions made at various levels, including the spinal cord and brain. In a robotic prosthesis (Figure 27-4) the energy source is typically a battery, the actuator is typically an electric motor, the transmission is usually a gear drive, and types of feedback vary, from simple wires to microprocessors.

Power

The most important characteristic of a power source is its energy-to-weight density. Other important characteristics include maximum discharge and recharge rate, the ease of recharging, and the safety of the power source in the event of a failure.

Nickel cadmium batteries are slowly being replaced by lithium ion batteries, which offer triple the amount of energy for the same weight. Lithium ion batteries are standard for applications such as power drills. Lithium polymer batteries offer even better densities than lithium ion batteries because they require less packaging. They also conform more easily to a given space (they aren't required to be rectangular boxes and can follow limb contours), and so represent an ideal

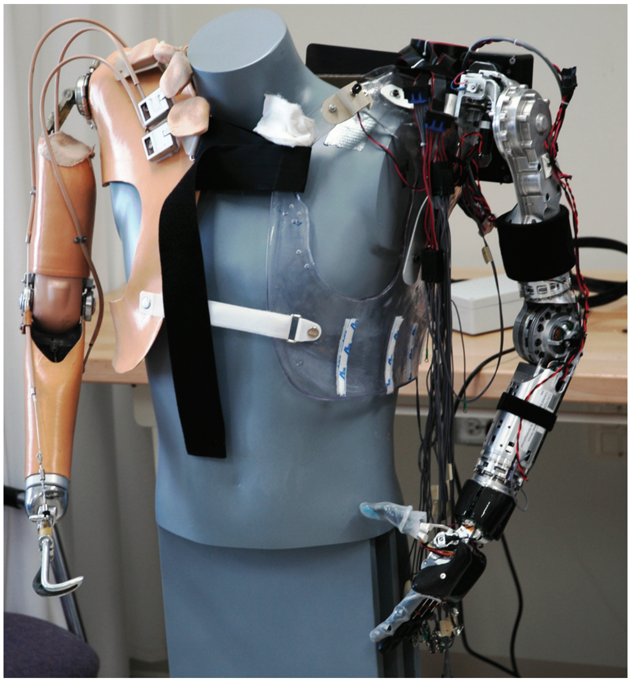

Figure 27-4. The left arm of the mannequin is an initial prototype of a robotic prosthetic arm designed to provide greater function to people who have had amputations at the shoulder, whereas the right arm is a traditional body-powered prosthetic arm. The robotic prosthetic arm was made by DEKA Research & Development Corporation (Manchester, NH) for the Defense Advanced Research Projects Agency (DARPA). It uses lithium ion batteries for power, brushless DC motors, and a variety of sensors including encoders, Hall effect sensors, and load cells.
Photograph: Courtesy of DEKA Research & Development Corporation.

power source for cosmetically appealing prostheses. Several recent nanoscale advances are now commercially available, and will likely be accepted into prosthetic use in the next 5 to 10 years. These batteries offer increased efficiency and hold the promise of increased power density. Methanol fuel cells, which have over ten times the density of lithium ion batteries, may soon be used to power laptops and could be inserted into prostheses in the near short term. However, they require improvement in several areas before commercial implementation, including temperature management, water management, and flow control.

The elbow flexion assist in the Otto Bock Ergo Arm (Otto Bock HealthCare) is an excellent example of a power supply that counteracts the power lost to gravity. Likewise, clutches resist gravity without consuming power, and so may be thought of as a power source. Human tendons are extremely efficient at storing and releasing energy, much more so than electrical regenerative systems such as those found in hybrid cars. A biomimetic advancement in prostheses is the introduction of artificial tendons, typically through a spring.[26] Denser power sources, however, have implications for other components. For example, the power density of lithium ion batteries makes the added complexity and weight of a clutch a detriment; the same result may be achieved with less added weight merely by using a slightly larger battery. If fuel cells become an option in prosthetics, other items such as elbow flexion assists may likewise become disadvantageous.

Actuators and Transmissions

As with the power source, the most important characteristic of an actuator is its power density. Several technologies such as hydraulic, pneumatic, and electromagnetic motors actually have greater power density, and therefore better performance, than human muscle. Other cutting-edge technologies, such as nitinol, artificial muscles, and piezoelectric motors have significantly lower power density than human muscle. As those technologies improve, they may provide new avenues of discovery for prosthetics (Figure 27-5).

Hydraulic motors have long been advocated as a better actuator than the more conventional electromechanical motor because they have triple the power density. Commonly used in large construction equipment such as cranes, hydraulic motors lose much of their advantage, however, when they are miniaturized to fit into a hand, and recent miniature hydraulics have been unable to perform as well as equivalent electromechanical motors.

A possible alternative for prosthetics is the "cobot," a concept developed for the automotive industry[27,28] in which a central motor spins continuously, and additional, tiny motors tap into the power created by the central motor to actuate numerous joints simultaneously. This setup is appealing because it allows for fast, independent movement of multiple joints, as well as power grasps by all the joints acting in unity, similarly to the human hand. Electromechanical motors waste a substantial amount of energy speeding up and slowing down for each individual movement, and cobots solve this problem. They are likely to be useful only for actuation of the fingers for patients with transhumeral amputation.

The most important characteristic of a transmission component is its efficiency, which in prosthetic devices ranges from 30% to 95%. Planetary gears offer the highest efficiency rates, often over 90%, but are unable to withstand large torques in a small package. Helical

Figure 27-5. Intrinsic hand design, which allows such functions as the pinch-grip, created by the John Hopkins University Applied Physics Laboratory for the Defense Advanced Research Projects Agency (DARPA). All of the actuators are intrinsic within the space of the hand, allowing the device to be fit to patients with a long transradial amputation (actuator technologies such as hydraulics and cobots are excluded due to their large space requirements). 15 brushless DC motors are used to actuate 18 degrees of freedom.
Drawing: Courtesy of John Hopkins University Applied Physics Laboratory.

teeth and ceramic materials improve efficiency and reduce noise, although increasing cost. Harmonic drives, used in the LTI Boston Digital Arm System (Liberating Technologies Inc, Holliston, Mass) provide significant speed adjustment in a single stage. However, they are not as efficient (70% maximum) as planetary gears, and they are noisier, although recent developments have made them significantly quieter in the Touch Bionic elbow (Touch Bionics, Livingston, United Kingdom). Other concepts, such as Ikona gears (Ikona Gear International Inc, Coquitlam, British Columbia, Canada) and cycloid gears, face similar problems.

A promising development is continuously variable transmission (CVT), which can optimize the gear ratio to achieve maximum performance or efficiency in a variety of situations. The Otto Bock DynamicArm (Otto Bock Healthcare) uses a CVT, as does the cobot. CVTs typically involve increased cost and complexity, and often necessitate an additional motor. Several suggestions for CVTs in prostheses without the need for additional motors and electronics have recently been proposed.

Sensors and Controls

The ability to sense various torques allows such features as CVT, auto-grasp during a slip, advanced control schemes such as impedance control or minimum jerk trajectories, maximum power efficiency, and adaptive stance control of the knee. Sensor-based control is what transforms robotics into mechatronics, and it is in this area that the field of prosthetics will likely grow in the next 10 years. Microcontrollers are becoming increasingly small—many powerful microcontrollers are now smaller than a nickel—allowing for precise control schemes to optimize any feature. As microprocessors become more integrated, different components may be able to communicate and provide feedback; for example, feedback in the socket–residual limb interface could allow adaptation of the socket shape based on the type of gait or phase of the gait cycle.

Mechatronic technology in which power transmission is isolated from signal acquisition is readily available. As researchers and industry alike continue the paradigm shift from conventional robotics to mechatronics, prostheses will exhibit increased power and dexterity without increases in weight. Although prostheses will admittedly become more complex, and in some ways more fragile, mechatronics, coupled with new power sources such as fuel cells, will provide a platform for a new surge of innovation in the field of prosthetics.

SUMMARY

Many advances in the last 20 years have had a remarkable impact on the function of prostheses, more so for lower limb than upper limb prostheses. Significant recent advances, including the shrinking size of microprocessors and new types of batteries, have created a new level of technology, now standard in the commercial sector, that should have a substantial impact on the future of prosthetics. The one area where success has been limited is socket suspension. Although commercial companies have devoted attention to this area, prosthetic interfacing requires substantial investigation and innovation to be part of an entire system superior to today's prostheses. The future of artificial limbs will certainly be both challenging and exciting, and should lead to improved quality of life for end users.

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