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Upper Limb Prosthesis: A Functional Replacement for the Biological Limb?

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Abstract

The 21st century continues to produce major advancements in prosthetic limb technology. Specifically, improvements to the myoelectric prosthesis have helped numerous upper limb amputees, especially transhumeral patients. Targeted muscle reinnervation surgery has allowed for more seamless control of the prosthetic device by creating new control centers for the unused nerves of the residual arm. Additionally, improvements in pattern recognition technology have enabled transhumeral amputees to gain more natural control of the prosthesis and consequently better imitate a biological limb. Another important development is in regards to the configuration and placement of electromyography electrodes on the amputee's body. Using high-density electrodes implanted totally beneath the patient's skin have dramatically improved accuracy and performance of the electromyography readings. One of the most current and promising developments has been targeted sensory reinnervation. Preliminary studies have shown that this surgery can provide a dual flow of both motor and sensory information simultaneously between the patient's residual limb and the prosthesis. Studies also indicate that using osseointegration surgery to connect the prosthetic device directly to the patient's bone has improved its performance and made it more comfortable for the user. Finally, by undergoing extensive training and rehabilitation under the guidance of therapists knowledgeable with upper limb prostheses, transhumeral amputees can gain remarkable skills in prosthetic limb locomotion. Further advancement is required but research continues at a quick pace in improving prosthetic devices so that one day they can truly replace biological limbs.

Introduction

In 2005, there were 1.6 million amputees residing in the US, with that number expected to double by the year 2050. Of that number, 41,000 people live with major upper extremity limb loss (Ziegler-Graham, et. al. 2008). The loss of a limb is a devastating experience but an amputee's quality of life can be dramatically improved with the use of a prosthetic device. Creating a truly functional prosthetic has been, and continues to be, a tremendous challenge. The importance of providing patients with advanced prosthetics and thereby enabling them to function normally can't be understated. This is especially true for upper limb amputees (ULAs) who are severely inhibited in accomplishing even simple everyday activities. For example, transhumeral amputees require a prosthetic device that can provide full function of the elbow, wrist, and hand. The objective of this paper is to familiarize the reader with the current prosthetic technology, as well as discuss the areas where further advancements are required in order to equip transhumeral amputees with the full range of motion, sensory input, and practicality of a true biological limb.

Methods

Research papers and articles were obtained primarily through databases such as ProQuest, Ebsco, and PubMed accessed through the Touro College library. Google Scholar was also used to search for pertinent material. Relevant keywords were used to mine for source material and the references found within them were further retrieved as additional sources. The librarians of Touro College were also extremely helpful in gaining access to articles which aren't publicly available via the web.

Available Upper Limb Prosthesis

Prosthetic limbs can be classified into the following two categories: body-powered and myoelectric. The former uses harnesses and straps attached to the patient's residual limb and body to move the artificial prosthesis. In the case of a transhumeral amputee, manually locking the joints would be necessary to switch between functions, such as movement of the elbow, wrist, and hand. The terminal device is usually a mechanical hook, but can be interchanged for many useful tools to fit the patient's specific task. The approximate cost of such a device is about $7,000 (Resnik, et. al. 2012). This form of prosthetic, while inexpensive and simple to use, is limited by the patient's own strength. Additional disadvantages include limited ability to perform relatively simple movements, moving only one joint at a time, and having an inhuman-like appearance. Even so, body-powered prostheses are still widely used by about 30% of ULAs today (Ostile, et. al. 2012). Most patients, however, will choose to use the more advanced, battery powered myoelectric prosthesis. One of the great advantages of this prosthesis is its ability to bypass the amputee's limited strength and instead use an external, artificial power source to enable movement. Additionally, the myoelectric prosthesis uses electromyography (EMG) signals to control the operation of the artificial limb, unlike the manual body-powered prosthetic. This is possible due to the neuro-muscular system which remains intact in the ULA's residual arm even after amputation (Sudarsan, Sekaran, 2012). It's this EMG signaling which allows the myoelectric prosthesis to interact so seamlessly with its wearer. Unfortunately, the cost of a transhumeral myoelectric prosthesis can be as high as $100,000 (Resnik, et. al. 2012).

EMG Signaling in Myoelectric Prostheses

The nervous system is made up of billions of neurons, all connected throughout the body. These neurons act as a communications pathway through the means of electrical signals and neurotransmitters at synapses. An electromyograph measures the strength of the action potentials with the use of an electrode placed at target skeletal muscle. Skeletal muscle is composed of contractible bundles of cells attached to bone.

The muscle's contractions control skeletal movement, usually induced voluntarily by impulses transmitted through the neuronal network to the motor neurons. The transmission occurs through the depolarization of the muscle fibers to generate an electric current, thus allowing the EMG signals to be measured (Raez, et. al. 2006). When an amputee is fitted with a myoelectric prosthetic, electrodes that measure EMG activity are placed at a single pair of flexion and extension muscles on the residual limb. A ULA's myoelectric prosthesis then retrieves the EMG signals generated by these two muscles to promote locomotion. However, the prosthesis is limited to controlling only one joint at a time. To switch from one joint to another (e.g. elbow to wrist), the patient must co-contract a pair of muscles, thereby signaling to the prosthesis to switch joints. A common pair used by a transhumeral amputee is the biceps brachii and triceps brachii. Alternatively, a patient may also use a remote controlled by shoulder or foot movement to switch joints. The strength of the EMG signal produced at these sites determines the prosthesis's velocity. For example, the amputee may use a biceps contraction to close the prosthetic hand, and a triceps contraction to open it, thereby promoting movement singularly controlled by the patient's nervous system. However, this becomes increasingly less intuitive with higher levels of amputation due to diminished levels of residual muscles available in the arm. For example, transhumeral amputees must use the biceps/triceps to control all distal prosthetic functions, as depicted in figure 1 (Cheesborough, et. al. 2015). Operation of the terminal device, wrist, and elbow needs to be done sequentially which besides being a very slow and cumbersome process, also requires much cognitive oversight because the same biceps/triceps need to move even the arm muscles not natively controlled by them (Kuiken, et. al. 2004, Carlsen, et. al. 2014). To allow for more seamless use of the myoelectric prostheses, an innovative surgery termed targeted muscle reinnervation (TMR) was introduced.

Targeted Muscle Reinnervation

The concept of targeted muscle reinnervation surgery was first introduced in the year 2004 to help a patient with bilateral amputations of the shoulders gain further control of the prosthesis (Kuiken, et. al. 2004). TMR surgery utilizes nonfunctional muscles as amplifiers for the patient's dormant nerves that were originally attached to the amputated limb. This enables the nerves to produce signals in those muscles, thus providing a source for intuitive prosthetic locomotion. For example, conventional control of a myoelectric prosthesis for a ULA with a transhumeral amputation is with EMG signals from the biceps brachii, as well as from the triceps brachii. Granted, this may provide intuitive control of elbow flexion and extension, but not forearm supination/pronation, nor hand opening/closing. These movements require cumbersome mode switches because the limited residual muscles must control physiologically unrelated movements. (Cheesborough, et. al. 2015, Carlsen, et. al. 2014,

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Kuiken, et. al. 2009, Zhou, et. al. 2007). Luckily, however, the median, ulnar, and radial nerves of the upper arm remain intact even after amputation (see figure 2), and consequently motor commands for the missing limb continue to travel through the residual nerves. Through TMR surgery, these nerves can be transferred to innervate other muscles in the body. Specifically, the median nerve is transferred to the short head of the biceps muscle to allow for hand closing (or pronation), while the distal radial nerve innervates the lateral head of the triceps to provide signaling for hand opening (or supination), as depicted in figure 3 (Carlsen, et. al. 2014). Ergo, through the use of TMR surgery patients will have gained four myoelectric electric sites in place of the standard two (figure 4). This allows for very intuitive control of the prosthesis; attempting to flex/extend the elbow causes the native contraction of the long head of biceps/

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triceps, while attempting to close/open the hand activates the short head of the biceps/lateral head of triceps which have been newly innervated by the median/radial nerve, respectively. Since there are more than one head to the biceps and triceps, one of each can be sacrificed as a recipient signal amplifier. This would not sacrifice the intuitive elbow flexion/extension signals that's provided by the remaining biceps/triceps muscles with native innervation via the musculocutaneous and radial nerves, respectively. Additionally, the four distinct EMG signals can be used to simultaneously control multiple joints, thus avoiding the traditional and tedious mode switching which is normally required (Cheesborough, et. al. 2015). While this use of TMR greatly increases a patient's control of the prosthesis, it's still limited to two simultaneous degrees of freedom: elbow flexion/extension and hand opening/closing. Further movements like wrist rotation still require cumbersome and unintuitive mode switches. However, by applying pattern-recognition techniques together with TMR surgery, substantially more motor control can be extracted from the reinnervated muscles (Zhou, et. al. 2007). Unfortunately, a difficulty that remains even post TMR surgery is separating the distinct amplitudes of the surface EMG signals on different muscles so that the prosthesis can recognize the intended movements of the amputee (Schultz, Kuiken, 2011). Additionally, further study is required to perfect the safety and long-term efficacy of TMR surgery, as well as making it more widely available to the masses.

Pattern-Recognition Techniques

Targeted muscle reinnervation provides a rich source of motor control information. In traditional TMR surgery, the median nerve is transferred to control hand closing, and the radial nerve to control hand opening. In contrast, a non-amputee's body will normally use these nerves to innervate dozens of muscles in the forearm, wrist, hand, and fingers. The goal of pattern-recognition techniques is to enable an amputee to control all these movements in the myoelectric prosthesis simply and dexterously. High-density electrode arrays are placed over the patients reinnervated target muscles as the muscles attempt many different motions involving the elbow, wrist, hand, and fingers. The specific patterns produced by the combined EMG signals are processed by software which

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deciphers which specific movement is being performed, hence the name "pattern-recognition". Detailed mappings of EMG amplitudes across the reinnervated muscle site of a TMR patient show distinctive patterns of activity as the subject attempts a variety of thumb, finger, and wrist movements. The pattern-recognition software has been shown to be 95% accurate in predicting a patient's 16 intended arm movements (8 degrees of freedom). To highlight, without pattern-recognition the conventional myoelectric control methods can only use EMG amplitude at specific myoelectric control sites, and ergo can't take advantage of the true complexity of information. Accordingly, the muscles reinnervated by the median and radial nerves operate only hand opening/closing. However, by using pattern-recognition software, information can be extracted about the subject's desire to perform wrist flexion/extension/rotation, and even movement of the thumb, index finger, or digits (Zhou, et. al. 2007). Further investigation was accomplished in 2009 that demonstrated pattern-recognition control for real-time use of myoelectric prostheses (Kuiken, et. al. 2009). A very brief explanation of how pattern-recognition techniques works is as follows: patients provide example contractions for each of the prosthesis movements (e.g., elbow supination, hand close, etc.), and the algorithm learns which EMG patterns correlate to each intended movement. Thus, when a patient later desires to move the prosthesis, the algorithm predicts the desired movement from the previously learned pattern of EMG signals (Cheesborough, et. al. 2015). This starkly contrasts to conventional EMG readings in that pattern-recognition doesn't simply use EMG signal amplitudes, but rather utilizes numerous EMG recordings to globally classify the patient's intended movements. The use of pattern recognition enables TMR patients to significantly outperform conventional nonpattern-recognition in the following two tasks: 1) a box and blocks task, and 2) a clothespin relocation task. Both of these tasks are validated and standardized measures of gross hand function first developed by occupational therapists. The box and blocks task requires the patient to move one inch blocks from one compartment to another during an allotted time period, while the clothespin task requires the movement of clothespins from a horizontal bar to a vertical bar also during an allotted time period (Mathiowetz, et. al. 1985, Kuiken, et. al. 2004, Miller, et. al. 2008). Patients moved 40% more blocks and completed clothespin relocation in 25% less time when using pattern-recognition over conventional myoelectric control. Additionally, patients' personal preference favored pattern-recognition over conventional control (Hargrove, et. al. 2013).

Electromyography Electrode Configuration

Though TMR surgery, along with advanced pattern-recognition, can provide vast amounts of neural information, it requires the use of a high density (HD) electrode array with over 125 electrodes placed over the reinnervated muscles. The placement of these electrodes is clinically challenging, and even after placement, the input of electromyography signals is slow. Preliminary studies show that by using advanced electrode selection algorithms, the number of electrode placements can be radically reduced to just a dozen. These electrodes can provide sufficient neural information to classify the user's intended movements with 99.1% accuracy in regards to 8 basic joint movements (elbow, wrist rotation, wrist flexion/extension, hand open/close). In a 16-class analysis which includes 8 additional finger movements, the classification accuracy was 93%. It's important to note that as the number of applied electrodes decreases, exact electrode placement becomes increasingly more integral. Thereupon, it's important to keep electrodes stably located over muscles, while being cautious to place them in the most accurate positions possible (Huang, et. al. 2008). Further studies show that by increasing electrode distance, as well as their orientation in regard to muscle fibers, pattern-recognition performance can be improved in the event of electrode shift (Young, et. al. 2011, Young, et. al. 2012). EMG signals are an integral mechanism for helping ULAs to gain full use of their myoelectric prosthesis. Therefore, ensuring that accurate readings can be obtained repeatedly and accurately is essential.

Implanted EMG Sensors

Though advancements in electrode configuration have greatly enhanced the accuracy of readings, they still have severe limitations such as poor skin contact (thus causing electrode liftoff), skin impedance changes due to sweating, lack of repeatable electrode placement due to day-to-day donning, as well as wire breakages (Weir, et. al. 2009, Pasquina, et. al. 2015). Hence, developing methods to solve these multitudes of issues are of the upmost importance. One method showing great promise is the use of fully implanted sensors beneath a patient's skin to ensure accurate EMG readings. These sensors are cylindrically shaped, and about 16 mm long (Figure 5). Each of these tiny sensors are capable of magnetically transmitting vast amounts of data directly to the retrofitted prosthesis. Furthermore, the ability to place these electrodes directly within residual limb muscles allows for stronger and more reliable signals that remain static despite body movement and sweating. Additionally, in the case of a transradial amputee these implanted electrodes present the possibility to record data from superficial and deep muscles simultaneously, allowing for more intuitive control by providing signals from the actual muscles responsible for hand and wrist locomotion prior to amputation (Pasquina, et. al. 2015). Unfortunately, a major technological issue with this system that still requires further research is reducing power consumption, and thus enabling the patient to have a portable prosthesis which can last a full day of use without the need for recharging (Schultz, Kuiken, 2011).

Targeted Sensory Reinnervation

No prosthesis can be called a true replacement of a biological limb without providing sensory feedback to its user. Tactile sensation is one of the earliest developed and basic human senses, providing a rich source of information about environ-

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mental stimuli. However, even when a patient uses an advanced myoelectric prosthesis they're still reliant on their limited visual feedback, wherefore hindering natural control of the prosthesis. Surprisingly, one of the reasons why body-powered prostheses continue to see widespread use is because the wearer can sense its movement through the cables attached to his body (Marasco, et.al. 2009). Therefore, proving tactile sensory information to the amputee is integral in providing a lifelike prosthesis. Unexpectedly, a potential source for proving this feedback was first discovered accidentally, as an unintended result of TMR surgery on a bilateral shoulder disarticulation amputee. After undergoing TMR surgery to transfer his residual brachial plexus nerves to the pectoralis muscles, touching the skin overlying the reinnervated muscles produced sensation in different areas of his phantom limb (Kuiken, et. al. 2004). With this knowledge, the targeted reinnervation surgery was extended to include reattaching sensory nerves as well, dubbed targeted sensory reinnervation (TSR). In the reinnervation surgery of a short-transhumeral amputee, the distal ends of the patient's supraclavicular and intercostobrachial cutaneous nerves were attached to the ulnar and median nerves, respectively (see figure 6). Six months after the operation, the patient reported sensation in her phantom hand when her reinnervated pectoralis muscles were stimulated. All modalities of cutaneous sensation were present including graded pressure, thermal feedback, vibration, and edge detection (i.e. sharp vs dull). Stimulation of each of these sensations within the reinnervated region was interpreted by the patient as occurring in her missing hand (Kuiken, et. al. 2007a). Further studies have similarly shown how sensory feedback can be felt by an amputee post targeted reinnervation surgery (Kuiken, et. al. 2007b, Schultz, et. al. 2009). However, the above mentioned studies have been limited mainly to patients with shoulder-level amputations who underwent targeted reinnervation surgery to reinnervate the brachial plexus to the pectoralis muscle group. Since a transhumeral amputee still needs the residual nerves to innervate the upper arm it's unfeasible to simply transfer the brachial plexus to reinnervate the pectoralis muscle group. To help solve this issue, a recent study has attempted to extend the scope of TSR surgery to a transhumeral patient. By using an improved variation of the TSR surgery, along with an incorporated sensory feedback device, a patient can now feel, and accordingly coordinate, the strength of force applied by the myoelectric prosthesis when handling an object, without auditory or visual stimuli. Previously, TMR patients simply obtained sensory reinnervation directly on top of the reinnervated muscle sites, which can lead to over-crowding when placing all the necessary hardware and EMG sensors. Hence, the ability to place the reinnervated sensory site distant from the reinnervated muscle site, but close enough to be viable, is a tremendous advancement in creating a viable sensory feed-back system for myoelectric prosthesis users. During the TSR surgery, the transhumeral patient's median and ulnar nerve are located and their high sensory nerve content fascicles isolated. These

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fascicles are dissected out of the main nerve trunk, transected distally, and coapted to the interocostobrachial cutaneous nerve and axillary nerve, respectively (see figure 7). The remainder of the nerve trunks are used to reinnervate portions of biceps and triceps as done in a classical TMR surgery. In addition to creating two spatially separated wide spread areas with discrete sensation for individual digits in the two nerve territories, called hand maps (see figure 8), the patient is able to utilize this sensory feedback to execute tasks while operating a myoelectric training arm, without having to rely on visual guidance or auditory cues. Furthermore, the above mentioned over-crowding problem is alleviated with this innovative surgical technique, as the sensory fascicles are directed to cutaneous areas distant from the muscle electrode sites. In the aforementioned study, the patient showed sensory feedback when gripping and releasing a ball, detected the difference between small and large blocks, as well as their difference in stiffness. Additionally, the patient discriminated between levels of applied force to the reinnervated area. Finally, the study demonstrated the ability to have a dual flow of motor and sensory information simultaneously between the patient's residual limb and the prosthesis. Additionally, further research is required to create a portable and wearable device that can viably transfer all the sensory and motor information between the prosthesis and its wearer. This was a single case study of a transhumeral patient and further investigation is required to test the efficacy of TSR with a real myoelectric prosthesis, as well as whether the sensory pathways will remain long-term (Herbert, et. al. 2014, Zuo, Olson, 2014).

Osseointegration

An unfortunate occurrence amongst amputees is prosthesis

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abandonment which can occur when patients refrain from wearing their prosthetic device due to problems including lack of comfort, stability, and durability. Mean rejection rates as high as 45% and 35% were observed for body-powered and electric prostheses respectively in pediatric populations, while adult populations had somewhat lower rates of 26% and 23%, respectively (Biddiss, Chau, 2007). However, by performing an osseointegration surgery which directly attaches the prosthesis to the patient's bone, one avoids the need for an unwieldly socket. This enables the prosthesis to always fit firmly, comfortably, and correctly, consequently giving the patient a more natural prosthetic limb to mimic the amputated biological one. The implant system includes a threaded titanium implant, which is inserted intramedullary into the transhumeral amputee's humerus bone, as depicted in figure 9 (Jönsson, et. al. 2011). As of yet, the FDA has not approved osteointegration trials for ULAs in the US, though one European group has successfully implanted devices in over 100 patients around the world (Cheesborough, et. al. 2015). Important to note is that after the osseointegration surgery, the patient must adapt to having a permanent appendage abutting from the limb.

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Rehabilitation and Prosthesis Training

Prosthesis training during rehabilitation directly affects an individual's level of function, and thus providing post-op amputees with proper instruction on how to use their prosthetic limb is vital. Training with therapists knowledgeable in upper limb prosthetic components and control is a significant portion of prosthetic rehabilitation leading to functional success of the ULA (Carlsen, et. al. 2014). Important to note is that fitting a patient with a congenital upper limb absence within 11 months of age leads to a greater acceptance than when fitted at an older age. Similarly, individuals fitted with a prosthetic 3 months after injury are less likely to reject the prosthetic device than patients fitted 6 months after surgery (Biddiss, Chau, 2007). Consequently, it's important to fit the patient with a prosthetic device and start the rehabilitation process as soon as possible. The rehabilitation process can be classified into a three-phase process. Phase one promotes healing of the residual limb wound, starting at the time of injury and continuing until all wounds have successfully closed and are infection free. The length of time spent in this phase varies depending on the extent of the patient's injury, but approximately three weeks after injury phase two begins and introduces pre-prosthetic training. The rehabilitation goal of pre-prosthetic training is to prepare the patient to receive a correctly fitting and functional prosthesis. This begins upon wound closure and ends with procurement of a preparatory training prosthesis. Patients will receive physical therapy to achieve improved flexibility and strength, as well as to educate them in avoiding incorrect postures that may lead to overuse injury of the upper body. Additionally, they learn how to perform activities of daily living, like writing, with just one hand when the prosthesis is unavailable. The third and final phase begins prosthetic training with the goal of the prosthesis becoming an integrated part of the patient's life. The therapy's focus is to help the amputee master the mechanical actions required for prosthetic control and eventually achieve independence in all activities of daily living. To help further this goal, the patient is fitted with varied types of prosthetic devices to gain experience accomplishing many different tasks so as to gauge and refine his skill sets when operating diverse types of prostheses. Hence, many patients will own multiple prosthetic devices and will use them accordingly for different tasks. The amputees are also trained in how to care for their prosthetic devices, to put on and remove them by themselves, as well as perform even complicated activities of daily living (Smurr, et. al. 2008). The rehabilitation for a post targeted muscle reinnervation surgery patient is somewhat more complicated, since each nerve that's being used for reinnervation contains numerous motor neurons. These neurons control many muscle fibers that work in conjunction to create nerve actions and thereupon move the body. For example, the radial nerve innervates hand extensor muscles, wrist extensor muscles, and supination muscles. However, a surgeon can't be certain exactly which nerve fibers will reinnervate the new target muscle. Hence, the patient must first attempt to perform all the actions controlled by the transferred nerves in order to see which will actually develop and innervate the muscle. The first noticeable reinnervation will usually occur at about 3 months after surgery. At this point, the patient can finally begin exercises to strengthen the reinnervated muscle over the next few months, followed by the patient learning to elicit strong, reliable EMG signals for the myoelectric prosthesis to receive. Whenever possible, the most intuitive movements that yield strong and reliable EMG signals will be used to move the prosthesis. As an example, the patient's attempt at extension of the phantom hand (radial nerve) hopefully will produce the strongest and most physiological appropriate signal for prosthetic hand opening, therefore making prosthesis movement intuitive for the subject. Over the long rehabilitation process, it's integral for the success of the patient that the occupational therapists, physical therapists, and prosthetists understand the principles of TMR, peripheral nerve distribution, specifics of the surgery, as well as the different possible post-op outcomes for each patient (Stubblefield, et. al. 2009). This will enable an amputee to truly gain the most from his prosthetic device and thereby return to functioning as fully and naturally as possible.

Conclusion

Science continues to make great strides in advancing prosthesis technology and thus increasing the quality of life of countless amputees. Electromyography signaling and targeted muscle reinnervation surgery continues to pave the way for leading edge prosthetic limbs. Advanced pattern recognition software is constantly being improved and perfected, while targeted sensory reinnervation surgery stands at the forefront of current scientific research in providing upper limb amputees with truly advanced replacements for their amputated biological limbs. Of course, additional work is needed to improve the control algorithms so that the amputee may interact seamlessly with his myoelectric prosthesis. Additionally, further study is needed to test the efficacy of wireless, implantable EMG electrodes. Osseointegration surgery remains a promising new method to comfortably suspend a transhumeral amputee's prosthesis. Additionally, targeted sensory reinnervation helps produce a real-time, dual flow of mechanical and sensory information between the prosthesis and its wearer. One of the biggest challenges remaining is to create a way to minimize power consumption of the prosthesis, while still providing its wearer with all the technology needed to provide the full range of motor output and sensory input of a real limb. Additionally, the life-time cost of providing a patient with a prosthesis can be astronomical and further advancements are needed to lessen the cost so that it can be a viable clinical option. The human body is a wonder and even a simple task like typing on a keyboard is truly a wonderment of seamless interaction of neurons and muscles. Hence, though a current myoelectric prosthesis is indeed an advanced appendage, it's still far less advanced than one's natural biological limb. Overall, however, the future seems extremely hopeful in one day providing a transhumeral amputee with a fully functional prosthetic limb to truly replace a lost biological one.

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