From Peg Legs to Bionic Arms: The Technologies and Policies of Prosthetics

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On my honor, I pledge that I have neither given nor received help on this assignment.
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Abstract

First, this paper will discuss the history of prosthetics and look at technologies that have been applied in the field over the years. Then, it will explain the modern development of electromyography technology and its potential application for prosthesis control. Secondly, it will examine the implications of prosthetics advances in society as well as the effects it can have on professional sports, specifically by looking at the case of Oscar Pistorius. Then, it will suggest technologies that will be viable for the future to solve the preeminent problems facing computer-controlled prostheses. Finally, it will discuss policy changes to assist in the regulation and use and of prostheses in competition.

In the 2012 Summer Olympics, Oscar Pistorius made history as the first athlete to compete in the Olympics without legs. That is, he ran using prostheses instead of natural flesh and bone. What many don't know was that his road to qualification for the events he competed in (100 meter, 200 meter, and 400 meter) was more arduous than the usual series of national and international competitions that are required. Pistorius also had to get through the Olympic Court of Arbitration of Sport (CAS) and the International Association of Athletics Federations (IAAF), the governing bodies that regulate international sporting laws. Because there was no precedent of how to handle a competitor with prostheses, the court had to generate a decision based on its own scientific data and studies. These studies consisted of a series of examinations of Pistorius's gait and speed that clearly demonstrated that he would not be fast enough to defeat his able bodied competitors. The question of eligibility for athletes using prosthetic devices calls to attention the broader question of the comparative capabilities of prosthetic limbs and natural limbs. Pistorius's prostheses were just customized pieces of carbon fiber in the place of his lower legs, but newer prostheses are beginning to incorporate computer control and self-contained power sources.

This paper will begin by discussing a history of prostheses, as well as problems encountered by early and modern prostheses technologies. Next, the paper will discuss EMG technology and its application in prosthetics. Then, it will look at the effects improving technology can have on society, especially in professional sports by examining the case of Oscar Pistorius. Next it will put forth suggestions for future solutions for prevalent problems with prosthetic design. Finally this paper will make suggestions for international sports policy regarding prosthesis technologies.

Prostheses have been in effect as long as organized civilizations have existed. Most early prostheses, however, were designed more for cosmetics than for practicality. For example, the oldest evidence of prosthetics in use is a wooden big toe that was found on the remains of an Egyptian noble woman (Clemens, 2008). It was strapped on to the foot to give the appearance of a toe, but it is just a static reproduction. As technology advanced, prostheses became more practical. There are accounts of a Roman general who used a metal arm with a shield attachment to continue his military career after a debilitating injury (Clemens, 2008). Along a similar vein, the 14th century yielded more simple and static devices such as the infamous peg legs and hook hands made popular by pirates suffering from swashbuckling injuries. Mobile and controllable devices did not appear until the 16th century when Ambroise Pare created a hinged hand and a leg with a locking knee (Clemens, 2008). The most difficult problem facing these ancient prosthetics designers, and even modern engineers, is control. Many clever designs surfaced, including straps connecting prostheses to existing limbs. Despite this, the dexterity of prosthetic appendages was limited by the rudimentary control technologies available.

To solve the problem of finer control for prostheses, modern technologies can tap into bioelectrical signals, which are the body’s own natural system for internal communication and control. Electrical signals can be found in the body in the form of nerve impulses and muscle activations. Retrieving data directly from the nervous system, a process called Electroencephalography (EEG), is difficult and ineffective as signals from nerves are very weak and are easily superseded by background noise (W. Lee, Interview, November 8, 2014). Collecting signals from muscle activations, Electromyography (EMG), is much more effective because the signals are orders of magnitude stronger than EEG (Chappell, 2003). EMG data, as with all bioelectric data, is collected through electrodes that are usually placed on the skin. The signals correspond to the groups of muscles activated, the force of activation, and the fatigue experienced by the muscles. Because all of these factors are highly dependent upon an individual's condition, it can be very difficult to accurately create a program to interact with an EMG sensor to differentiate between muscle activations. Despite this, there are examples of EMG signals being used to control devices in lieu of conventional controllers. For instance, the Virginia Commonwealth University Bio-interfaced Nanoengineering lab used EMG signals from a user's forearm to pilot a small drone using simple statistical analyses of EMG data (W. Lee, Interview, November 8, 2014).

Although controlling prosthetic devices through computers is not achievable with current technology, passive prostheses that are made from materials that mimic the functions of biological systems are popular, especially in the field of sports. Pistorius's "Cheetah Blade" prostheses are, for example, made of carbon fiber that reproduces the springing motion accomplished by the achilles tendon during running (Grogan, 2012). When his candidacy for the 2012 Olympics came into question, a scientific analysis of his running was done to determine if his prostheses provided him with an unfair advantage over the able-bodied athletes. The IAAF appointed a team and oversaw the details of the procedure. They began by filming a specifically staged race with several high definition cameras placed at different angles. An examination of the films showed that Pistorius had a slower acceleration than the other runners, as well as less bounce in his stride (Crincoli, 2011). In addition to filming him running, Pistorius's oxygen consumption was measured to determine his comparative energy consumption. His legs were found to consume 25% less energy than an able-bodied runner (Camporesi, 2012). This, coupled with the different stride characteristics, changes the portions of the race where he is the fastest. In a 400-meter race, able-bodied runners are fastest in the first and second 100 meters, and slower in the third in fourth due to muscle fatigue. Pistorius, on the other hand, is fastest in the second and third because of his slower acceleration and lower energy consumption (Crincoli, 2012). Therefore, even though he has less energy consumption than an able-bodied runner, his prostheses still do not give him an advantage because of their clumsier acceleration and inability to generate additional force while running.

While athletic prostheses are reasonably effective and can allow individuals to participate in activities that might otherwise be impossible for them, they lack the versatility for everyday life. Sports prostheses are purpose-built for their specific sport, and therefore can focus on mimicking just the motions needed from the muscles used for that sport, much like Pistorius's Cheetah Blades that replicate the Achilles tendon. For daily activities such as writing, typing, or eating, much more dexterity is needed. Prosthesis users need to be able to control individual digits and be able to move throughout the full range of normal motion. This requires more than the passive prostheses that are commonly used today. In addition, passive prostheses often put additional stress on residual limbs that causes joint and muscular issues. For example, Kobe University conducted a study of oxygen consumption during comfortable walking speed for subjects with prosthetic hips. The subjects had an average oxygen consumption rate of 18.3 mL/kg/min at a comfortable walking speed (Chin, 2012). To put that into perspective, an average-sized person walking at a similar speed has an oxygen consumption rate of 6.3 mL/kg/min (Jette, 1990). This demonstrates that even though for a sprinter, oxygen consumption might be reduced because of mechanical assistance, for more practical applications like walking, prostheses cause much greater stress for users.

The clear solution for increased energy consumption in prosthesis users would be to utilize powered prostheses to make up for the energy contributions of missing appendages or joints. An example of such a prosthesis is being developed by Hugh Herr, a biomechanical engineer at Massachusetts Institute of Technology. He lost both feet in a climbing accident, and was unsatisfied with conventional passive prostheses for everyday living. To fix this, he developed a series of powered springs that can mimic the energy contributions of the Achilles tendon during walking. The system uses a motor in the back of each foot that feeds energy into springs placed where the Achilles tendon would be that release energy when the user pushes his foot off the ground (Piore, 2010). The system is revolutionary, but suffers from a problem encountered by many similar computer assisted designs: power supply. In order to provide enough power for the bionic foot, the user needs to either carry a 13 pound backpack of batteries or remain connected to the wall (Piore, 2010). Since neither of these sources of power is practical, powering advanced prostheses remains a significant problem.

In addition to problems with power supply, computer controlled prostheses suffer from the linear and conditional thinking of traditional “hard” computing. In hard computing, specific conditions elicit specific reactions from a program. For example, when you press a “w” button on the keyboard, a “w” appears where your cursor is. This is a repeatable and consistent condition that will continue to get the same results. However, electrical signals from EEG and EMG are not consistent and repeatable (Chowdhury, 2013). Several different factors can change the signal received from a muscle or nerve activation during use. As muscles become more fatigued, higher levels of activation are required to achieve the same amount of work. The electrodes used to collect the data can be covered with sweat or shift slightly from their position. Skin thickness underneath the electrode can even change while a prosthesis is in use. Current computing methods cannot adequately take into account all of these factors that change the signals received (Xie, 2014). As well as being inconsistent and unrepeatable, biological signals are often indifferentiable from each other. For example, a plot of electrical charges taken from an arm after clenching the fist and bending the wrist will look almost exactly identical (Figure 1). Statistical analyses of the incoming data, such as discriminant analyses and Markov tests, are not specific enough to generate consistent differences between different activations, again because of the unpredictability of the EMG signals (Xie, 2014).

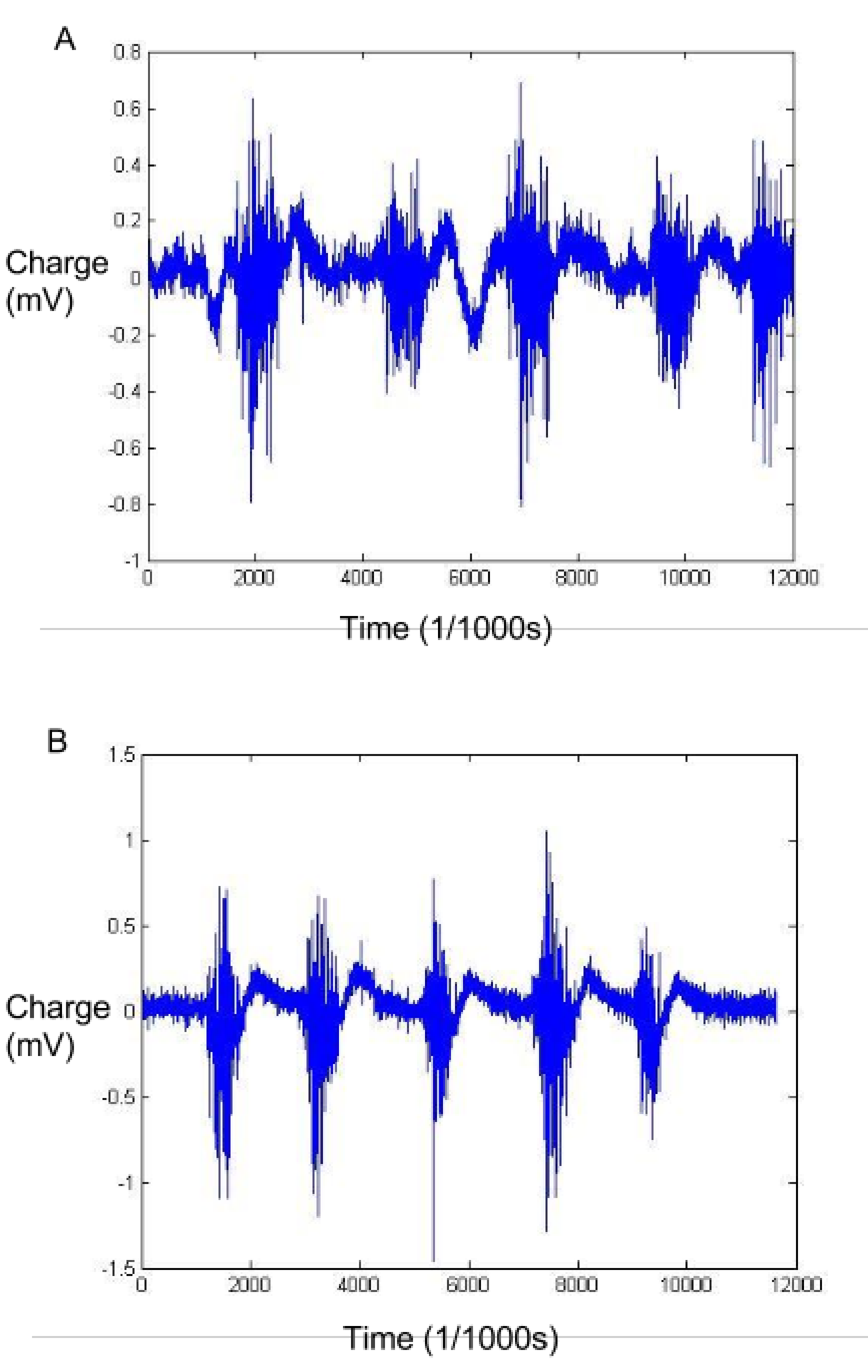
There are, however, solutions for these technical problems facing computer-controlled self-powered prostheses. Power-hungry electrical motors can be replaced with the use of chemically-fuelled muscles. The majority of power consumption in a powered prosthesis is, of course, from the motor that drives its motion. Instead of using motors to approximate the effects of a muscle, chemically powered muscles can mimic the action of the muscle fibers themselves. Small systems of carbon nanotubes filled with hydrogen sulfate can flex and bend in a similar way to actual muscles (Figure 2). This is achieved through a chemical reaction between the hydrogen sulfate and an electrode on either end of the system, one providing oxygen and the other providing hydrogen (Ebron, 2006). Because hydrogen and oxygen are the consumed components in the reaction, air and water are the only supplies needed to continue fueling the muscle, making it simple to keep the system operating throughout its use. In addition to providing an energy-efficient and easy to fuel source of motion, the carbon nanotubes can tolerate large amounts of stress, even larger than what natural muscle fibers can handle. The stress generation capability for a carbon nanotube system is nearly 500 times that which is typical for a human skeletal muscle (Ebron, 2006). This means that in addition to providing a replacement for muscles in lost limbs, these systems can augment the abilities of the user.

Control remains a significant problem for the creation and implementation of computerized prostheses because of the unpredictability and unrepeatability of biological signals. This obstacle can be be surmounted, however, by using “soft” computing systems instead of traditional computing systems. Soft computing systems are superior to a hard system in EMG analysis applications because they are capable of acquiring specific knowledge for a particular domain, uncertain reasoning, and adaptation to a time varying environment (Xie, 2014). This means that a soft system can “learn” an individual’s muscle activation patterns and how they change throughout the day, and adapt the control elements of its program based on this knowledge. There are many means of creating a soft computing system, but a hybrid of several can achieve the highest level of adaptability and accuracy. Hybrid systems have been demonstrated to reach 99% accuracy with up to 10 different motions in muscles as small as those powering the hand and fingers (Xie, 2014). Integration of soft computing techniques into prostheses will effectively allow for the precision and control necessary for computer-controlled powered prostheses.

The increasing abilities of prostheses to replace the function of lost limbs is approaching a level where it may exceed natural limbs. This raises the question of how to deal with such advances in competitive scenarios. If someone is born with the inability to participate in an activity but can become physically able to through technology, should they be disallowed from a competition because of that technology? On the other hand, allowing technological devices shifts the focus away from an athlete's own abilities, and more towards the budget and skill of the engineers providing their prostheses. Current rules and regulations regarding international competition set in place by the IAAF do not allow for any "improper technical devices" to be used to assist an athlete (Crincoli, 2011). This is a very vague ruling that makes no real decisions about the future of prosthetics in competition. A much more applicable policy would be one that looks at the candidates individually. For example, Pistorius was initially denied the ability to compete based on his use of technical devices. It took a lengthy appeal to get a true scientific analysis of his athletic abilities and get an informed decision on his eligibility. Instead of requiring tremendous effort on the part of the competitor, the IAAF should have a scientific body in place that is prepared to examine and make eligibility decisions for athletes in unique situations. Such a body would have use for determining more than just the influence of technical devices on individual's eligibility, but for other cases such as surgeries and pharmaceutical assistance as well.

Making such decisions can be very difficult. What criteria can you use to judge differences between athletes? Every competitor is unique, meaning that some athletes will just be better than others. During Pistorius's testing, it was determined that he did not have an unfair advantage in part because it was proven that his times were not fast enough to win (Crincoli, 2011). If everyone was tested using similar criteria, Usain Bolt would have to be prohibited because he is the "fastest man on Earth." Obviously, natural ability cannot be used to exclude athletes from competition, so there must be a differentiation between what is an athlete's natural ability and what is artificially contributed. Because of this, prostheses should be judged based on their energy contributions to the activity they are used for. Pistorius's Cheetah Blades are passive devices that simply spring like an achilles tendon when his thigh muscles press downward. This does not contribute any unnatural force to the act of running, and therefore should be permissible. However, prostheses that employ self-contained power sources or generate force in a way that the body does not naturally should not be allowed for competition. Expanding prosthesis capabilities can be addressed by regulatory bodies in professional sports by preparing reasonable criteria and putting a panel of experts in place to examine specific cases.

Figure 1



A: Graph showing charges from repeatedly clenching fingers on the right hand into a fist. B: Graph showing charges from repeatedly bending right wrist to the left. Each fluctuation is one repetition. Data was retrieved with skin-mounted electrodes.

Figure 2

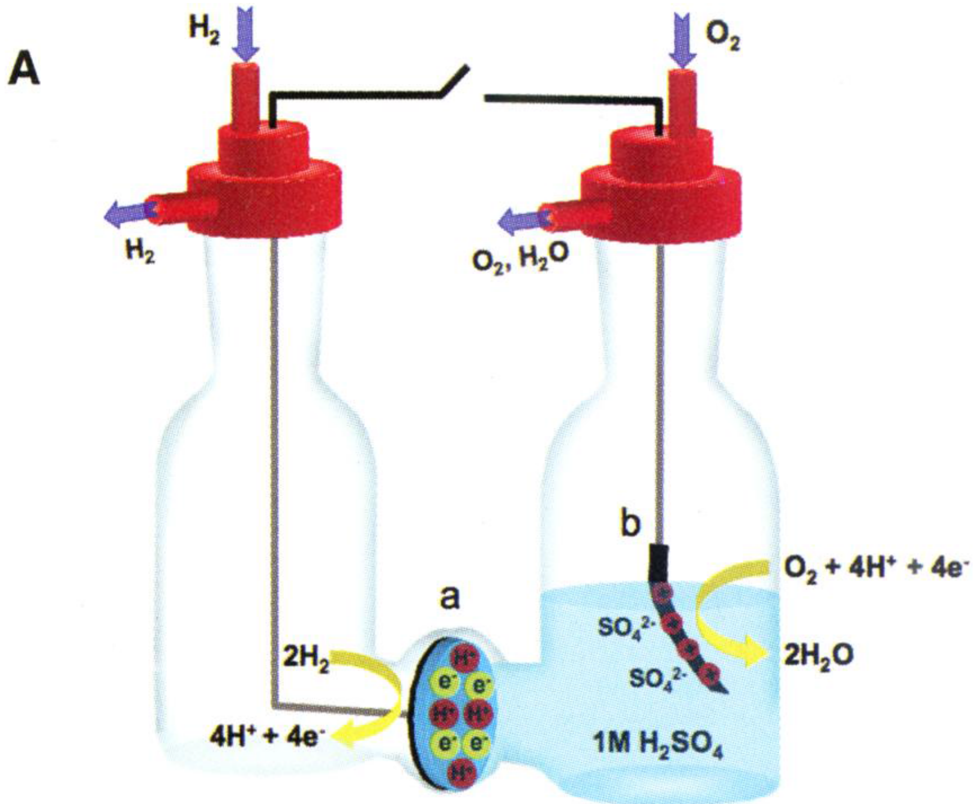


Diagram showing the concept of the chemical reactions required to power a nanotube muscle.

References

Bragaru, M., Dekker, R., Geertzen, J., & Dijkstra, P. (2011). Amputees And Sports. *Sports Medicine, 41*(9), 721-740.

Rehabilitating amputees is a significant application of prosthetic limbs. This article discusses how loss of a limb through medical amputation, congenital defects, and destructive accidents can decrease quality of life. Individuals without limbs suffer from mental and physical health issues mainly due to their inability to engage in physical activity. The use of artificial limbs to allow patients to become active and repair their health is also explained in this article.

Camporesi, S. (2008). Oscar Pistorius, enhancement and post-humans. *Journal of Medical Ethics, 34*(9), 639-639.

This article discusses studies conducted on Pistorius's physical abilities. It references various statistics on his running speed and energy consumption. In addition, it presents the issues of morality involved with using prostheses to enhance athletic performance. The "purity" of the Olympic games if enhanced athletes were allowed to compete would questionable, but so is the idea of asserting that disabled athletes are not "pure."

Chappell, P. (2003). Advances in the control of prosthetic arms. *Technology and Disability, 15*(2), 57-61.

Though slightly outdated this article provides a series of summaries of the works of Jim Nightingale and David Simpson, two researchers in the field of advanced prostheses. Nightingale's work pioneered the usage of adaptive computing to create user-specific EMG control programs for individual patients in need of prosthetic limbs. Simpson used an apparatus that bypassed some of the difficulties of using EMG signals for prosthetic control by drawing upon signals from areas not adjacent to the prosthetic itself.

Chin, T., Kuroda, R., Akisue, T., Iguchi, T., & Kurosaka, M. (2012). Energy consumption during prosthetic walking and physical fitness in older hip disarticulation amputees. *The Journal of Rehabilitation Research and Development, 49*(8), 1255-1255.

This article presents a study of prosthetic limb applications amongst elderly patients. It investigates the exertion experienced by hip-disarticulation suffering unilateral amputees during walking. The study examined the oxygen consumption while walking at a comfortable speed. After the testing, patients reactions to using prostheses in public settings were examined and compared to the energy consumption to determine how comfortable the users were with their prostheses.

Chowdhury, R., Reaz, M., Ali, M., Bakar, A., Chellappan, K., & Chang, T. (2013). Surface Electromyography Signal Processing and Classification Techniques. *Sensors, 13*(9), 12431-12466.

EMG signals are becoming increasingly important in many applications, including clinical/biomedical, prosthesis or rehabilitation devices, human machine interactions, and more. However, background noise in the signals is a major obstacle for any application. Detection, processing and classification analysis in EMG is very desirable because it allows a for an evaluation of technological findings. This paper reviews two possible methods; first: the pre-processing method for eliminating artifacts via appropriate preparation at the time of recording EMG signals, and second: an explanation of the different methods for processing and classifying EMG signals. This study then compares the numerous methods of analyzing EMG signals in terms of their performance.

Clements, I. (2008, June 5). The history of prosthetic limbs. Retrieved November 19, 2014, from http://science.howstuffworks.com/prosthetic-limb1.htm

This article includes a moderately detailed description of past prosthetic technologies citing many archeological examples. In addition, it uses examples draw from ancient historical texts that detail the science and medicinal practices of the time.

Cowan, R., Fregly, B., Boninger, M., Chan, L., Rodgers, M., & Reinkensmeyer, D. (2012). Recent trends in assistive technology for mobility. *Journal of NeuroEngineering and Rehabilitation, 9*(1), 20-20.

This paper surveys recent work in assistive technology to improve mobility for persons with a disability, drawing on examples observed during a of research sites in Europe. This article investigates the seamless integration of the capabilities of the user and the assistive technology. This improved integration spans diverse technologies, including powered wheelchairs, prosthetic limbs, functional electrical stimulation, and wearable exoskeletons. Improved integration is being accomplished in three ways: 1) improving the assistive technology mechanics; 2) improving the user-technology physical interface; and 3) sharing of control between the user and the technology. The article provides an overview of these improvements in user-technology integration and discusses whether such improvements have the potential to benefit individuals with impaired mobility.

Crincoli, S. (2011). You can only race if you can't win? *Texas Review of Entertainment & Sports Law, 12*(2), 133-187.

This article provides background on Oscar Pistorius's running career and the Olympic rules and regulations that affect his ability to compete. It also addresses the process of

his appeal to the Olympic court of Arbitration. It presents the evidence used to support Pistorius's case and statistics that compare his performance to that of other athletes.

Duncan, D. (2014, February 21). The cyborg Olympic games. *Newsweek Global*, 110-114.

David brings up several good points about the relation between the spectator's perception of the sporting events and what regulatory organizations put in place. People want to see amazing athletic feats, and regardless of exterior factors will watch the most extreme events they have access to. The article also discusses the emergence of prosthetic technologies that are equal to and even superior to natural appendages. Hugh Herr and Oscar Pistorius are cited as examples of these developments.This article contains very current and relevant information, drawing information from decisions by the Olympic committee and well-known athletes and scientists.

Ebron, V. (2006). Fuel-Powered Artificial Muscles. *Science, 311*(5767), 1580-1583.

The article goes in-depth into currently developing technologies for artificial muscles. These muscles have powerful applications in the fields of robotics and prostheses. Conventional artificial limbs use electrical motors powered by batteries, but providing sufficient power using these systems are not weight or space efficient. Using fuels can provide greater energy potential to create stronger artificial limbs.

Grogan, A. (2012). Paralympic technology. *Engineering & Technology, 7*(8), 28-28.

This article focuses on the use of modern technology in Paralympics. It features the application of carbon fiber blades that are interfaced with the existing limb of an athlete. Moreover , it mentions that Paralympic athletes are sometimes knowledgeable than their trainers concerning the use of modern technology citing examples of wheelchair athletes that use high technology devices such as velocimeters.

Huang, S., & Ferris, D. (2012). Muscle activation patterns during walking from transtibial amputees recorded within the residual limb-prosthetic interface. *Journal of NeuroEngineering and Rehabilitation, 9*(1), 55-55.

In order to analyze the actual effectiveness of EMG signals in prosthetic applications, this article examines EMG signals from amputees residual limbs during a series of tests. The study involved having the amputees walk on a treadmill at varying speeds with EMG electrodes attached to their residual limbs. The resulting data was then examined using statistical analyses and a comparison to control subjects. the results showed that the amputees' signals were differentiable at higher speeds, but very similar at lower speed, meaning that there is need for additional processing for lower speed gaits.

Jetté, M., Sidney, K., & Blümchen, G. (1990). Metabolic equivalents (METS) in exercise testing, exercise prescription, and evaluation of functional capacity. Clinical Cardiology, 13, 555-565.

This source explains the metabolic equivalent, or MET. It is a unit for measuring athletic activity through oxygen consumption. One MET is equal to 3.5 mL/kg/min of oxygen consumption. In addition, this article list the average oxygen consumption for numerous athletic activities such as walking, running, and swimming.

Kazamel, M. (2013, February 12). History of Electromyography (EMG) and Nerve Conduction Studies (NCS): A Tribute to the Founding Fathers (P05.259) -- Kazamel et al. 80 (1001): P05.259 -- Neurology. Retrieved November 17, 2014, from http://www.neurology.org/cgi/content/meeting_abstract/80/1_MeetingAbstracts/P05.259

This article summarizes the discussions and presentations on a seminar on EMG developments. It discussed milestones on EMG development such as the discovery of biological electronic signals. In addition, it credits each discovery to the scientists and organizations involved in its finding.

Nicolelis, M. (2012, September 1). Mind in motion. *Scientific American*, 58-63.

The article discusses neuroprosthetic technologies which use brain waves to control and manipulate computer cursors and robotic limbs. It examines the work of neuroscientist Miguel A. L. Nicolelis and his colleagues as they plan to develop an exoskeleton to be worn and controlled by a paraplegic at the 2014 World Cup, and how bioelectrical engineering can be used to interface signals created by the brain's cortex and computer systems. Additional information is presented on how the exoskeleton will operate using electrodes implanted in the motor cortex.

Piore, A. (2010, November 1). The bionic man. *Discover*, 50-57.

Piore's article focuses on the experiences of Hugh Herr, an MIT bio-technologist and founder of iWalk who had both of his feet amputated at 17. He created his own highly advanced prosthetic feet so he could continue his athletic pursuits, specifically rock climbing. Through a combination of advanced materials and innovative designs, he developed an interchangeable foot system that can surpass normal human capabilities.This article provides specific evidence from Herr's own studies and incorporates substantial background about the evolution of his work and the conditions that inspired it. All of its data is from current studies and based on published reports and interviews.

Resnik, L. (2014). Self-reported and performance-based outcomes using DEKA Arm. *Journal of Rehabilitation Research & Development, 51*(3), 351-361.

This article presents a study of the DEKA arm, a prosthetic arm for upper-limb amputees. The arm include many high-technology features, but its real-world effectiveness needs testing. The study examined its properties in daily life for 26 prosthetic users and compared it to the effectiveness of conventional prostheses. Activity performance and dexterity were used to evaluate the differences between the various prostheses.

Sawers, A. (2012). Microprocessor controlled knees. *Journal of Rehabilitation Research & Development, 50*(3), 273-314.

This article examines the use of microprocessor-controlled knees for individuals with transfemoral limb loss. It examines existing publications that address computer-controlled prostheses, and attempts to compare the outcomes for patients using microprocessor-controlled knees and non-computerized knees. It uses several criteria including metabolic energy expenditure, activity, cognitive demand, gait mechanics, environmental obstacle negotiation, safety, preference and satisfaction, economics, and health and quality of life to evaluate the results of prosthetic knee use.

Wolff, A. (2011, August 8). Prosthetics: Between man and machine. *Sports Illustrated*, 50-53.

This article reports on advances in prosthetic technology and U.S. veteran amputees' participation in the Paralympic Games and other competitions. Walter Reed Army

Hospital's Military Advanced Training Center for physical and occupational therapy as well as other specific research laboratories that are investigating prostheses are discussed. The departments of Defense and Veterans Affairs' role in financing prosthetic research is also examined as a major source of funding for prosthetic research.

Xie, H. (2014). Hybrid soft computing systems for electromyographic signals analysis: A review. *BioMedical Engineering OnLine, 13*(8).

EMG signals are a powerful tool for driving human-machine interfaces, such as prostheses. However, EMG signals have many inconsistencies and are often difficult to differentiate. This article addresses the use of soft computing to sort EMG signals and increase the accuracy of analyzing the signals. If technology can achieve this, EMG sensors will be viable for control of prostheses, enabling patients to use artificial limbs with the same ease of a natural limb.