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History and Future of Rehabilitation Robotics

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History and Future of Rehabilitation Robotics

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Abstract

With recent technological advances it has become possible to develop advanced artificial limbs for people with disabilities. This report gives a brief history of the field of Rehabilitation Robotics, and then reviews eight currently produced (either experimentally or commercially) robotic devices designed to assist patients with limb loss or in need of skeletal-muscular assistance. After detailing the use and operation of each device, this report assesses each device on the basis of eight criteria: cost, accessibility, maintainability, training, adaptability, safety, environmental concerns and technological possibility. Each device was given a ranking based on those criteria, and on the basis of those rankings, predictions were made as which technologies are most successful today and most likely to be the basis of future development. This report concludes that the technology contained in the I-Limb is the most likely to be enhanced and further developed.

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Introduction

In the United States, there are approximately 1.7 million people living with limb loss. It is estimated that one out of every 200 people in the U.S. has had an amputation. There are currently 4.7 million people would benefit from an active lower limb orthosis due to the effects of stroke, 1 million post polio, 400,000 due to multiple sclerosis, 200,000 due to spinal cord injury, and 100,000 due to cerebral palsy (Creg, Neri 2008). Due to these numbers, engineers have been performing research in order to combine robotics with the rehabilitation field; this new field is called Rehabilitation Robotics. In the following report we will analyze the most recent robotic devices being developed or already in use within this field. Some of the designs which will be discussed have been created to enhance the performance of the human body while others were created for medical treatments in order to improve daily life of people who have been affected by a degenerative disease or traumatic injury. In this report we will start off with a brief look at the history of the field, what led up to today's innovations. Then the paper will turn and look at individual devices, giving a brief introduction to the device and its purpose before diving into a few of the technologies that comprise the device. That section will close with projections of the future, specifically what pieces of the device our group believes can be utilized further in the near future. Finally the ratings for each device based on a number of criteria which will aid in making projections towards the future of robotics within the rehabilitation field. These ratings will also provide additional information about other aspects that interest the consumers, such as safety and/or overall cost.

Objectives

The objectives for this project are to discuss and analyze the recent developments in the field of rehabilitation robotics, their applications and potential future. In order to predict how the future of this field will be shaped, one has to turn to the past. Only by briefly examining the history of the field including past devices and past trends, can projections for the future be made. In addition to exploring the past, one also has to examine the devices of today. By looking at the present day devices it is possible to determine the focus of the field as well as the technologies being currently used and in development. These technologies are the most critical aspect when predicting future devices. Even when the devices become obsolete the technologies that made them will continue to evolve, or at least be used to further improve and inspire the creation of new technologies.

The technologies of the devices will help in determining which devices were successful. However, to actually determine what devices were successful in the field they will be rated. The rating system used is based on a number of criteria; the criteria will be composed of the most important aspects of the field, such as cost, maintainability, etc. From the successful devices it will be possible to predict what technologies are worth utilizing and developing in this field.

Background

Rehabilitation Robotics has been defined a special branch of robotics which focuses on machines that can be used to help people recover from severe physical trauma or assist them in activities of daily living. This field has evolved from a more common field known as Rehabilitation Engineering. Rehabilitation Engineering is closely related to physical therapy and it utilizes its three main focus areas. The three main areas of physical therapy are the cardiopulmonary, neurological, and musculoskeletal. Cardiopulmonary therapy is dedicated to the treatment of breathing problems such as asthma and it helps to rehabilitate those who have undergone cardiac trauma. The neurological field mostly aims to help restore muscle control or to help foster muscle control in those born with little or none. Musculoskeletal therapy assists in strengthening and restoring functionality in the muscle groups and the skeleton, and in improving coordination. Though rehabilitation robotics has applications in all three areas of physical therapy, most of the work and development is focused on musculoskeletal uses of robotics. Recently the applications within the neurological field have been increasing with the advancements in robotic prosthesis.

In order to understand the most recent developments in the robotics field we must first understand the evolutionary process which led to our current technological status. As in the development of any other field, some ideas and inventions have worked and been expanded upon, while others have fallen by the wayside or become obsolete. During our research we'll be focusing in two of the most complex fields of Rehabilitation Robotics, exoskeletons and robotic prosthesis.

The history of rehabilitation engineering can be traced back to the development of functional prosthesis. Functional prosthesis can be considered the backbone of rehabilitation robotics. To this day the oldest functional prosthesis found has been the Cairo toe found in 2000 in a tomb near the ancient city of Thebes (Clements, 2008). Based on the way the linen threads were spun, it dates from 1295 to 664 B.C. The Cairo toe is considered a functional prosthesis since it is jointed in three places and according to the archeologists shows signs of wear. The toe was found attached to the foot of the mummy of a female between 50 and 60 years of age, the amputation site was also well healed. This can be a good representation of how little prosthetic limbs have changed throughout history. With the exception of very recent times, prosthetic devices have been constructed of basic materials, such as wood and metal, and held to the body with leather attachments.

Functional Prosthesis continued to evolve from regular joints to the use of springs and releases. One of these prostheses was the iron hand made for Gotz von Berlichingen. In 1508, Gotz von Berlichingen had a pair of advanced iron hands made after he lost his right arm in the Battle of Landshut. The hands could be manipulated by setting them with the natural hand and moved by relaxing a series of releases and springs while being suspended with leather straps. Similar hands were created by famous surgeon Ambroise Pare (Figure 1).

Figure 1: Iron hand designed by Ambroise Pare scienceblogs.com

There was very little advancement in the field of functional prosthesis until the end of the 17th century when Pieter Verduyn developed the first non-locking below-knee prosthesis in 1696. This design would later become the blueprint for current joint and corset devices. It wasn't until the late 1800's when the next major advancement in prosthesis was made. In 1868 Gustav Hermann made use of aluminum instead of steel to make artificial limbs lighter and more functional. However, the use of lighter materials wasn’t implemented until 1912, when Marcel Desoutter, a famous English aviator, lost his leg in an airplane accident, and made the first aluminum prosthesis with the help of his brother Charles, an engineer.

The advancements in functional prostheses have always been pushed forward during the times of war. During the American Civil War the number of amputations rose astronomically, forcing Americans to enter the field of prostheses. Similar to the Civil War, World War 1 also had an impact on prostheses. Although it did not foster any significant advancement in the field, the Surgeon General of the Army at the time realized the importance of the discussion of technology and development of prostheses. This eventually led to the formation of the American Orthotic & Prosthetic Association (AOPA). After World War II, veterans were dissatisfied with the lack of technology in their devices and demanded improvement. As result, the US government brokered a deal with military companies to improve prosthetic function rather than that of weapons. This agreement paved the way to the development and production of modern prostheses. Today's devices are much lighter, made of plastic, aluminum and composite materials to provide amputees with the most functional devices.

The field of Robotics in Rehabilitation Engineering officially started with the research into Powered Human Exoskeleton Devices in the 1960s. The research into exoskeletons devices began with science groups in the United States and Yugoslavia, each with a different goal (Dollar and Herr, 2008). The United States had been focusing its research in the development of technologies to augment the abilities of able-bodied humans which often focused on military applications. On the other hand Yugoslavia intended on developing technologies which would help improve the functions of physically challenged individuals. Despite the difference in the areas of research both countries faced the same challenges; the main one being the interface between the machine and the human operator.

In order to improve the interface between human and machine scientists and engineers have been focusing their research in the development of exoskeletons. An exoskeleton is a wearable robot with joints and links corresponding to those of the human body (Pons, 2006). The exoskeleton, as an assistive device, is also an external structural mechanism with joints and links corresponding to those of the human body. The human wears the exoskeleton, and its actuators generate torques applied on the human joints. In utilizing the exoskeleton as a human power amplifier, the human provides control signals for the exoskeleton, while the exoskeleton actuators provide most of the power necessary for task performance. The human becomes part of the system and applies a scaled-down force in comparison with the load carried by the exoskeleton. Integrating capabilities of humans and robotic-machines into a unified system offers numerous opportunities for developing a new generation of assistive technology.

The exoskeleton research in the United States can be traced back to 1965, when the US Department and General Electric developed HARDIMAN (Figure 2). HARDIMAN stands for Human Augmentation Research and Development Investigation and was intended to allow the wearer to lift 1,500 lbs (Bogue, 2009). This research was traced until the 1970s when one arm had been developed. This arm could lift 750lbs and responded accordingly to specifications, although it weighted three-quarters of a ton. Further research was made during the 1980s where an engineer at the Los Alamos National laboratory developed a strength-enhancing suit which took its commands through brain-scanning sensors in a helmet. Although

Figure 2General Electric's HARDIMAN dvice.com

the research had some possibilities for success the technology at the time caused some limitations. The computers weren’t fast enough to process the control functions necessary to make the suit respond smoothly and the energy supplies were not compact enough to be portable. Even though these two research devices failed, scientists have learned from them and the US Government is still interested in the military application of exoskeletons.

The Defense Advanced Research Projects Agencies’ *(*DARPA) interest in military exoskeletons has continued through Exoskeletons for Human Performance Augmentation (EHPA), a program founded in 2001 with the goal of increasing the capabilities of ground soldiers beyond that of a human. Over the duration of the EHPA program various institutions have shown progress in the improvement of exoskeletons. One of these institutions is the University of California Berkeley where the Berkeley Exoskeleton (BLEEX) was first unveiled in 2004 (Kazerooni, 2005). This system is design to give its wearer the ability to carry significant loads on his back with minimal effort. Although this system has been developed for military applications, the technology has potential for rehabilitation applications.

Potential applications could benefit members of both healthy and disabled populations. For many physical tasks, human performance is limited by muscle strength. People can only achieve so much in terms of strength and endurance. Exoskeletons could help in assisting people in many lines of work, firefighters could use them to move debris, construction workers could use them to lift and operate heavier machines and materials, and they could even be utilized by nurses in moving heavy patients around the hospital. The Department of Defense has also taken a great interest in the development of exoskeletons (Kazeroon, 2005). Building and equipping a soldier with an exoskeleton would allow that soldier to be able to not only to carry more armor and/or weapons but be able to travel farther and faster without becoming fatigued.

Muscle weakness is also the primary cause of disability for persons with a variety of neuromuscular conditions including stroke, spinal cord injury, muscular dystrophies, and other neurodegenerative disorders. The Hybrid Assistive Limb otherwise known as HAL is a full-body suit designed to aid people who have degenerated muscles or those paralyzed by brain or spinal injuries (Guizzo and Goldstein, 2005). In the most recent model, HAL-5's structure consists of a frame made of nickel molybdenum and an aluminum alloy (Figure 3). Further strengthened by plastic casing, the metal frame is strapped to the body and supports the wearer externally. Its several electric motors act as the suit's muscles to provide powered assistance to the wearer's limbs. This newest model improves on earlier versions of the exoskeleton, such as HAL-3's, in several ways. Previous prototypes helped ailing humans to stand up, walk, climb stairs, and perform a range of other leg movements. One user was able to leg-press 180 kg, about 400 pounds. HAL-5 adds an upper-body system that helps users lift up to 40 kg more than they normally could. Wearing the suit, a healthy adult male can lift 80 kg; roughly double what he can normally. Like many other exoskeletons HAL-5 and BLEEX are in the need for better power sources. An adequate power source is a big technological need; such as lighter, longer lasting, and faster recharging batteries then these suits could be useable by anyone. Some of the major limiting factors in the mass production of exoskeletons are technology, cost and size of the systems.

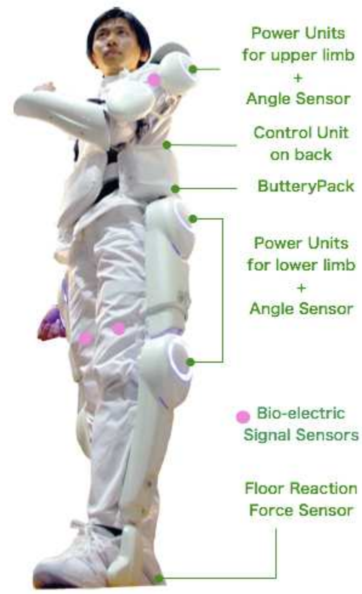

Figure 3 Hal-5 http://gadgetgui.de/blog/wp-content/uploads/2007/02/hal_unitpict.jpg

The research in the field of Rehabilitation Robotics has passed through many stages; some devices have come and gone with few obvious positive results. All however, have contributed to the volume of knowledge from which those now working in this field of research benefit. It is important not to forget the lessons of the past. The future of rehabilitation robotics is promising, with a number of technologies in development which promise even more efficient and groundbreaking results. As the technology develops, the area of discussion in this field increases which makes it necessary to provide a definition and information on some terms before we continue on to the main devices.

Definitions

Gait Rehabilitation

Often after a person suffers from a stroke, traumatic brain injury, a spinal cord injury or any other lesion of the human nervous system they lose their ability to walk. Fortunately due to the ability of the nervous system to be shaped, people still have the opportunity to re-learn walking to a certain extent by undergoing intensive rehabilitation. This rehabilitation procedure is what we refer to as gait rehabilitation (Lünenburger, et al 1996).

Electromyogram Controls

An electromyogram or EMG involves recording the electrical activity in muscles. An electromyogram measures the electrical activity of muscles at rest and during contraction. Nerve conduction studies measure how well and how fast the nerves can send electrical signals. Nerves control the muscles in the body by electrical signals known as impulses. These impulses make the muscles react in specific ways. Any movement involving the muscles and nerves requires electrical signals sent from the brain. For below-elbow prosthesis there are two sets of muscles that can provide signals to operate the prosthesis, these are the wrist flexor and extensor muscles. The wrist flexor muscles produce a signal which is used to close the prosthetic hand while the wrist extensor muscles provide the signals to open the prosthetic hand.

An electromyogram is read by inserting a needle through the skin into the muscle. The electrical activity is detected by this needle (which serves as an electrode). The activity is displayed visually on an oscilloscope and may also be displayed audibly through a microphone. This method is often used to test patient's electrical signals for abnormalities that are found in many neurological and muscular disorders. The EMGs used on the exoskeletons are read by multiple sensors that detect when an electrical current is being transmitted, the velocity of the signal, and the strength of the current.

The process of reading electrical signals is very useful in creating robotic prosthetics. The human body has two forms of electrical signals that are useful in the development of rehabilitation robotics. Electrical currents produced by the nerves and currents produced by the muscles, both are known as bioelectricity. Bio-electromagnetism refers to the electrical, magnetic, and electromagnetic fields produced by living cells, tissues, and organisms. These electrical currents are produced by the nerves and muscles when they perform an action. Cells store metabolic energy to do work. Bio-electromagnetism refers to the fields that are created from the electrical current produced by nerves impulses. Nerve impulses are changes in membrane potential, or the difference in electrical potential between the interior and exterior membrane of a cell. The electricity created is known as bioelectricity.

A myoelectric signal is an electrical impulse that produces contraction of muscle fibers in the body (SearchMobileComputing, 2005). The term is most often used in reference to skeletal muscles that control voluntary movements. Myoelectric signals are of interest to the developers of prosthetic devices, such as artificial limbs. These signals can be used to facilitate the operation of a computer using small voluntary muscle movements, such as blinking the eyelids.

These electrical signals are detected by placing three electrodes on the skin. Two electrodes are positioned so there is a voltage difference between them when a current occurs. The third electrode is placed in a neutral area, and its output is used to cancel the noise that can otherwise interfere with the signals from the other two electrodes. The output voltage is processed using a device called a differential amplifier, which multiplies the difference between two inputs. The output of this amplifier has much higher voltage than the signals themselves. This higher voltage, which produces significant current, can be used to control electromechanical or electronic devices (SearchMobileComputing, 2005).

When combining electromyograms with the use of prosthesis, scientists have started to make use of Bio-Cybernic systems. A of Bio-Cybernic systems is a system that allows a prostheses, that can record and read electromyograms, to act accordingly to the signals. A weak person would now be able to perform the toughest of tasks with the help of such a device. It would also be helpful in retraining people to use muscles that have been affected by degenerative diseases.

Phantom Limb Syndrome

Phantom limb syndrome is a sensation amputees have that their missing body part is still there. The brain has remained open to receiving input from those nerves even though the appendage is no longer there. Impulses from the brain to control the missing limb still travel down the neurons towards the sight of amputation. Scientists can use electronic sensors to pick up the control signals and relay them to a mechanical device (Saenz 2009).

Reinnervation and Sensory Feedback

Three of the systems that will be covered in this report use Targeted Muscle Reinnervation (TMR) as a controller and feedback mechanism these devices are the Smart hand, the Luke Arm and the Proto arms. Over the past years neuroscientists have been researching ways for the patients to use their chest muscles and skin to intuitively control a prosthetic arm and even to feel some pressure applied to the limb. Through their research the scientists discovered that patients were able to sense touch on the skin of the chest as if it were on the skin of the missing hand. Once this was discovered scientists at the Rehabilitation Institute of Chicago were able to map the sensitive spots on the chests to specific limbs.

Most of the functions of our body are driven by electrical currents from a part of our brain called the motor cortex. The motor cortex sends out the electrical impulses down the spinal cord through nerves into our muscles. These electrical impulses are sent through our bodies and cause our muscles to move. TMR involves surgically mapping the residual nerves from an amputated part of the body, this procedure was pioneered Dr. Todd Kuiken. The residual nerves are the nerves that connect the upper spinal cord to the 70,000 nerve fibers in the arm. In their normal layout, these travel from the upper spinal cord, across the shoulder, down into the armpit, and into the arm (Creg, Neri 2008). These nerves remain functional even after the arm is severed; the only difference is that they lose their sensory input.

In order to rewire the residual nerves one must make use of the pectoral muscles. These are the muscles located in the front of the chest, also referred as the anterior chest. These muscles normally remain intact once an arm is severed. In order to rewire the residual nerves Kuiken dissected the nerves from the armpit and threaded them under the clavicle in order to connect them with the pectoral muscles (Adee, 2007). The objective of TMR is to make the control of an artificial limb an intuitive process; this means that after procedure is completed the patients are able to use the arm by just thinking about it. When a patient thinks of an action signals are sent down the nerves formerly connected to the arm but that are now connected to the chest. The chest muscles contract in response to the nerve signals, the contractions are sensed by electrodes on the chest and the electrodes send signals to the motors of the prosthetic arm (Creg, Neri 2008).

Using TMR doesn't just allow the patient to intuitively control the prosthetic arm, but it also allows the patient to receive feedback through the prostheses. Rewiring the residual nerves allows the reinnervation of the skin near the chest area. When that skin is touched the patient feels as if he/she is being touched in the missing limb as well as the chest. Kuiken researched this phenomenon and was able to map the thresholds at which uncomfortable heat, warmth, cold, and painful electric shocks translated into these sensations in the missing fingers and hands (Adee, 2007). These results are believed to be the result of the brain's ability to adapt to a change in the body.

The research performed with TMR led to a new development. In order to improve the feedback for the TMR procedure engineers developed a synthetic skin. This skin was developed to transfer small increments of heat and pressure effectively. This skin allowed the transfer of stimuli within fractions of a second to the reinnervated chest area. This allowed the patient to feel as if their missing limb was being touched. Engineers and researchers at NASA, the National Institute of Aerospace (NIA) and the Oak Ridge National Laboratory (ORNL) recently created a synthetic skin that is both aesthetically pleasing and extremely sensitive and durable. This skin looks and feels like a human skin (Creg, Neri 2008). This skin was made out of rubber polymer with carbon nanotubes embedded within the polymers. The carbon nanotubes within the polymer also help transfer temperature quickly, since they have been shown to transfer heat up to 20 times faster than a polymer without similar carbon nanotubes. At the moment this synthetic skin is being tested with the Proto arm.

Rehabilitation Robotic Systems

Lower Extremity Exoskeletons

BLEEX

DARPA has been interested in military application of exoskeletons. Part of their research has been performed through Exoskeletons for Human Performance Augmentation (EHPA), a program founded in 2001 with the goal of increasing the capabilities of ground soldiers beyond that of a human. One of the projects being funded by DARPA is a $50 million, five-year program which began in 2001. This project resulted in the development of the Berkeley Lower Extremity Exoskeleton (BLEEX) (Figure 4) at the University of California Berkeley, and the Berkeley Lower Extremity Exoskeleton which was first unveiled in 2004 (Kazerooni, Steager, Racini, 2005).

Figure 4 BLEEX http://www.zamazing.org

This exoskeleton has been designed to be used by army medics in order to allow them to carry injured soldiers off a battlefield or for rescue workers to bring in food and first-aid supplies to areas where vehicles cannot enter. In other words this exoskeleton has been design to improve the performances of rescue personnel. The BLEEX system has been defined as a wearable robotic system. This is the type of system in which the human pilot does not need a joystick, button or special keyboard to control the device. Rather, the machine is designed so that the pilot becomes an integral part of the exoskeleton.

The BLEEX consists of mechanical metal leg braces which are connected rigidly to the user at the feet, and, a pair of metal legs frames the outside of a person's legs to facilitate ease of movement. This device also includes a power unit and a backpack-like frame used to carry a large load. The exoskeleton's vest is attached to the backpack frame and the engine. The machine has been designed to be user friendly. For example, if it runs out of fuel the exoskeleton can be easily removed so that the device converts to a large backpack. More than 40 sensors and hydraulic actuators have been designed into a local area network (LAN) which makes the exoskeleton similar to a human nervous system. The sensors, which are also included into the shoe pads, are constantly providing the central computer with information so that it can adjust the load based upon what the human is doing. The exoskeleton constantly calculates how the weight must be distributed so little to no load is imposed on the wearer (J. Mraz 2009).

The BLEEX system has been designed with four major components, each of which represents a different advancement in technology. These components are the power supply, the electric system, the Pseudo-anthropomorphic design and the control system. BLEEX was created to be an autonomously powered exoskeleton, for this reason it needs to have an onboard power supply. In order for it to be efficient the power supply needs to be autonomous, small and portable, but still able to power the exoskeleton's actuators, computer, and all the sensors. For this reason the engineers have developed a Hybrid Hydraulic Electric Power (HEPU) source which runs on regular gasoline and weights 1.4 Kg. The HEPU provides both electric and hydraulic power by using a two-stroke twin cylinder engine. An example of this design can be seen in Figure 5.

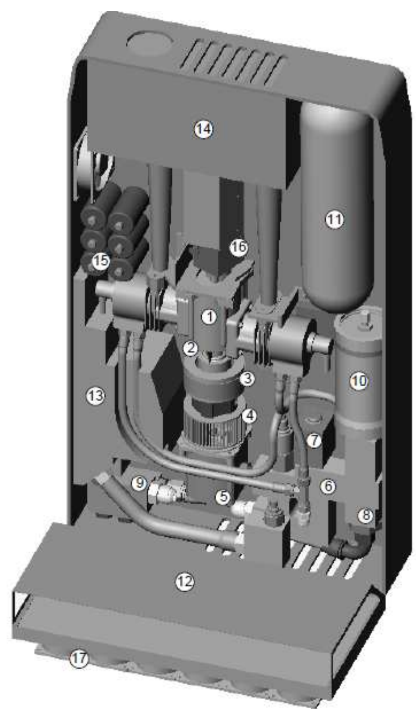

Figure 5 HEPU layout. Engine 1; shaft 2; alternator 3; cooling fan 4; gear pump 5; manifold 6; solenoid valve 7; filter 8; pressure transducer 9; accumulator 10; nitrogen tank 11; heat exchanger 12; hydraulic reservoir 13; muffler 14; batteries 15; carburetor an

Over the past years engineers have been concentrating on the development of hybrid power systems due to the demand for clean energy. The technology used to power the HEPU contains a hybrid power system similar to that being developed for hybrid vehicles. As mentioned previously the HEPU is designed with a two stroke, twin cylinder internal combustion engine. The engine uses a single shaft to power the alternator in order to generate electric power; it also powers a cooling fan and a gear pump which generates hydraulic power. The engine also contains a hydraulic solenoid valve which regulates the hydraulic fluid pressure by directing the hydraulic flow from the gear pump to the accumulator or the hydraulic reservoir. The accumulator has been designed with a free piston used to separate the hydraulic fluid from pressurized nitrogen gas. It also contains a carbon fiber tank which is used as a reservoir for the nitrogen gas (Chu, Andrew, H. Kazerooni, and Adam Zoss 2005). At the rate that hybrid technology is evolving it will become possible to create autonomous machines similar to the BLEEX exoskeleton in the near future.

The electronics of the BLEEX system is a very important technological component. The exoskeleton's body was designed as LAN (local-area network) that hosts the computers and sensors. The exoskeleton was designed with over 40 sensors with mixed analog and digital signals, which all go to a central processor. These sensors and actuators are on a network built into the body called ExoNET which transfers information via one wire. These sensors and hydraulic mechanisms function like a human nervous system, constantly calculating how to distribute the weight being borne and create a minimal load for the wearer. The ExoNET was designed to reduce the bulk and complexity of the wiring system.

One of the most important sensors within the BLEEX system is the new force sensor called the Hydraulic Human Powered Extender. This sensor is designed to detect forces by measuring an induced pressure change in a material of large Poisson's ratio. This sensor has been proven to have sensitivity larger to and also contain a smaller bandwidth than those of existing strain-gage-type sensors. This force sensor is well-suited for measuring large but slowly varying forces. It can be installed in a space smaller than that required by existing sensors. This sensor has been used to measure compressive forces up to 7,200 lbf and tensile forces up to 3,500 lbf. These special sensors, developed by Sarcos, feed data to a control computer that in turn commands the robotic limbs to move in harmony with the wearer's arms and legs without ever obstructing them. With the use of this sensor the BLEEX system allows the wearer to walk around in the 100-pound exoskeleton plus a 70-pound backpack and it feels as if he was carrying just five pounds. Such a technology can be improved for upper extremity exoskeletons (Kazerooni, H, Ryan Steger, and Lihua Huang 2006). This type of technology has great potential for military applications, with similar improvements in upper extremity applications it can allow engineers and scientists to create a full body exoskeleton similar to the one used by the fictional character Iron Man.

In itself the design of BLEEX can be considered a technological advancement. The BLEEX engineers chose a design that is almost anthropomorphic. This means the BLEEX legs are kinematically similar to a human's, but with fewer degrees of freedom than a human leg. Since a human leg and the BLEEX legs are not exactly the same, the driver is only connected to the exoskeleton at the feet and torso. If there were any more rigid connections there would be large forces imposed on the operator due to the kinetic differences. A second benefit of not completely matching the human and the exoskeleton is that it can be adjusted for various operators. The connection at the torso is made by using a custom vest. This vest was designed as method to distribute the forces between BLEEX and the pilot. This vest was made of several hard surfaces that are completely connected to each other using thick fabrics. The vest is attached to a ridged back plate which includes comfortable backpack-like straps. These straps grasp the operator and distribute the forces over the operator's torso, chest and upper back (Chu et al, 2006).

The final element is the control algorithm that runs the machine. This control algorithm allows the machine's movements to be synchronized with the pilot with minimal interaction force between the two. The control scheme obtains direct measurements from the human or from the human-machine interface through the sensors which are constantly receiving and sending information. If you walk forward, it walks forward; if you go backward, it goes backward; if you stop, it stops. This is done without requiring direct input from the human. The person doesn't have to drive the machine, the pilot simply walks, and the machine follows (Chu, Andrew, H. Kazerooni, and Adam Zoss 2006).

The BLEEX also contains a very important sub system; the hydraulic actuators (Seen in Figure 6) which are designed into a local area network (LAN) which makes the exoskeleton similar to a human nervous system. These hydraulic actuators are used to distribute the weight so that the least amount of load is imposed on the user. This hydraulic system was designed using clinical gait analysis data. This data provides information on how much power the human body uses to perform functions such as walking, running or even lifting weights. From this data it was noticed that humans expend the most amount of energy through the sagittal plane joints, which is why the BLEEX prototypes provide power to the sagittal plane joints. The clinical gait analysis was used to design the BLEEX

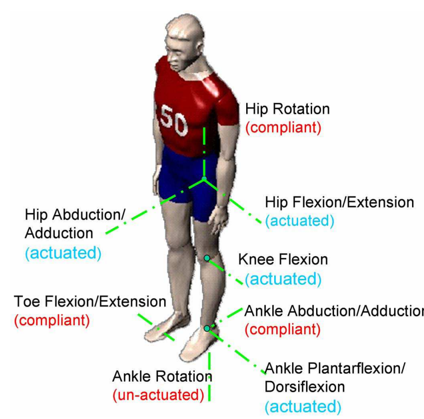

Figure 6 BLEEX Hydraulic Actuators (http://bleex.me.berkeley.edu)

actuation system under the assumption that BLEEX resembles a human's weight and volume (Kazerooni 2005). The hydraulic system within the BLEEX has a double purpose, the first as mentioned previously is to distribute the load throughout the system, and the second is to provide power to the system by using the HEPU.

LOPES (Lower Extremity Powered Exoskeleton)

Due to the recent development in the robotics field there have been more robotics devices dedicated to the mechanization of physical therapy. Robot mediated therapy becomes very useful in cases where the therapist's effort is very intensive leading to limitations, availability or in the worst case injury. In most cases even though the robotics systems are available a therapist will still be responsible for the nonphysical interaction and the observations of the patient's training. LOPES (Figure 7) is one of these robotic systems, it is implemented for gait rehabilitation by using a treadmill training system. The target group consists of people who have suffered a stroke and have impaired motor control. LOPES is designed to offer assistance in leg movements while keeping lateral balance. In order achieve this; the patient's limbs are connected to the exoskeleton so that robot and patient move in parallel (R.Ekkelenkamp et al. 2007). LOPES contain two extreme control modes which will aid the patients during the rehabilitation process. The first mode is the patient in charge mode. The goal during this mode is to minimize the interaction forces between the patient and the robot. In this

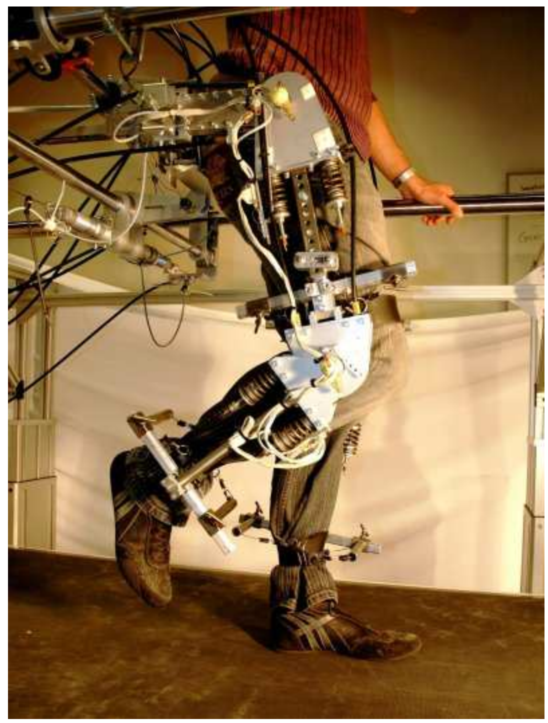

Figure 7 LOPES Exoskeleton http://www.bits-chips.nl/

mode the patient can walk freely without feeling the robot, in other words the robot provides no resistance or aid to the patient. The second mode is the robot in charge mode. During this mode the exoskeleton will take control over the functions which the patient is unable to perform. Under normal situations the exoskeleton will operate between these two functions depending on how much aid the patient needs.

LOPES uses joint trajectory during the gait cycles, during this cycle the robots offer uniform controls along the trajectory. With this control the patient receives support where is necessary. With this LOPES aims to support the patient where he needs assistance. This will lead to a more active participation from the patient’s side. The tradeoff for more active walking will likely be a smaller overall distance during therapy sessions.

LOPES system was developed using a series of Bowden cable driven series of elastic actuators. The Bowden cable is a type of flexible cable used to transmit mechanical force or energy by the movement of an inner cable relative to hollow outer cable housing. Springs were then used to cancel the non-linear effects of the Bowden cables. With this design after executing some tests engineers discovered that walking in LOPES does not significantly change muscle activation (EMG) measurements during walking (R.Ekkelenkamp, et al. 2007).

Bionic Hands

I-Limb

Touch Bionics is a Scotland firm that developed the I-LIMB Hand (Figure 8); this is a prosthetic hand with five individually powered fingers. The company, an Edinburgh medical device developer, is also making ProDigits partial hand prostheses, based on similar technology. The I-LIMB Hand is the most advanced bionic hand in the market, the hand looks just like a real hand with 4 fingers and a thumb, all of which can be moved to allow a grabbing action. This hand was designed with a few unique features. One feature can be seen in the design of the fingers; each finger contains a motor which means that each finger is independently driven and can articulate; another being that the thumb is rotatable through 90 degrees, in the same way as the human thumb. The skin of the hand has been implanted with two electrodes that pick up myoelectric signals. In order to control the I-LIMB a two-input myoelectric signal is used to open and close each finger. “Myoelectric controls utilize the electrical signal generated by the muscles in the remaining portion of the patient’s limb” (Touch Bionics). Myoelectric control is advanced control software that provides the device with both speed and grip-strength control. The patient then generates signals that control this device in a way that is similar to how traditional past devices would operate. To detect the small electrical signals that are generated by the patients remaining muscles in their limb, two small metal electrode plates are placed against the skin, which will pick up these small signals. A bit awkward at first, the myoelectric control system is quickly learned by patients and they are able to create these electric signals by simply flexing the appropriate muscles. The I-LIMB can perform a variety of unique grip positions that allow the user to balance power and precision as needed. Through the use of the myoelectric controls the user is able to individually extend each finger and with this function the user can type on a keyboard or push buttons. The hand also allows the user to grip different objects and is capable of stopping when a sufficient grip is achieved, allowing the patient to grip sensitive objects without crushing them (Touch Bionics). The grip control is achieved through a built-in stall detection system. This system tells each individual finger when it has sufficient grip on an object and, therefore, when to stop powering. Individual fingers lock into position until the patient triggers an open signal through a muscle signal (Touch Bionics).

Figure 8 I-Limb (http://www.touchbionics.com)

The I-Limb comes with custom cosmesis (Figure 9) design which makes the hand appear to be real. The cosmesis is made out of a semi-transparent material which has been computer-modeled to wrap every contour of the hand. This cosmesis serves a double purpose since it protects the hand from the environment and it brings an added dimension of personal comfort to the user. Touch Bionics has partnered with other companies in the development of cosmesis; some of these companies are ARTech Laboratories and LIVINGSKIN. The I-LIMB currently costs about $18,000, and is being used by over 600 patients.

Figure 9 I-Limb Cosmesis (http://www.touchbionics.com)

Clearly the I-LIMB is a marvel to be hold, but what can it offer to the future? Its biggest draw is how much emphasis was put on making it similar to a real hand, both in terms of look and functionality. The five individually powered prosthetic fingers ("powered digits") are a big step towards the future. Giving the person control over the individual joints that make up the limb not only makes the prosthetic more real, but also allows for a greater range of functionality. From feedback on Touch Bionic's site it has been noted that most the people using the I-LIMB really like the control they get over individual fingers. Our group believes this is an important technology that will be continued in the future, and adapted to a wide range of other prosthetics, moving the field one step further.

Shadow Hand

The Shadow Dexterous Hand (Figure 10) is an advanced robot hand system that reproduces all the movements of the human hand and provides comparable force output and sensitivity. This means it can pick up or handle small to medium sized objects and perform precision tasks.

Handling delicate objects like eggs is a task that, at the moment, can only be performed by human beings (Shadow Robot Company, 2009). The Shadow Hand is driven by 40 Air Muscles mounted on the forearm. These air muscles follow a biologically-inspired design principle in which tendons couple the air muscles to the joints. The hand contains integrated electronics at the base of the system. These electronics drive the pneumatic valves for each muscle and also manage corresponding muscle pressure sensors. The hand contains three actuation modes, an opposing pair of muscles permits full control and variable compliance of the movement for most joints. Conditionally-coupled drive is used for the Middle and Distal phalanges of the fingers to produce human movement characteristics.

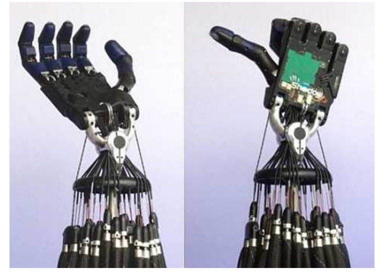

Figure 10 Shadow Hand (http://gizmodo.com)

In order not to break or bruise the objects a certain level of sensitivity and compliance is necessary, the Shadow Dexterous Hand excels in these areas through the use of we have implemented a variant optical sensing mechanism providing detection down to 0.03N with a moderately linear response (Shadow Robot Company, 2009).

The Shadow hand was developed by The Shadow Robot Company in London and is commercially available. Matthew Godden, senior robotics-design engineer for Shadow, said the hand costs more than $100,000, but the company has already sold a hand to NASA, Bielefeld University and Carnegie Mellon University (Olsen, 2007). The hand is used mainly in dealing in specialized circumstances, like environments that are not human friendly, but the hand is also studied and mimicked by many, in the development of assistive devices.

The entire system including hand, sensors, and motors has a total weight of 4 kg (about 8.8 pounds). The system is composed of three major subsystems: forearm, palm, and fingers.

Each component is built with a combination of metals and plastics. The forearm is made up of aluminum and resin shell; the palm is acetyl, aluminum, polycarbonate and the fingers are acetyl, aluminum, polycarbonate fingernails and polyurethane flesh.

The Hand is driven by 20 Smart Motor units mounted below the wrist which provide compliant movements (Shadow Robot Company 2009). The motors have a biological design; a pair of tendons links each Smart Motor to the corresponding joint of the Hand. Integrated electronics in the Smart Motor unit drives the high efficiency motor and also manages corresponding tendon force sensors. The Smart Motor unit is designed to ensure that the system is safe at all times. It monitors tendon forces and keeps them within defined limits and manages the temperatures preventing the overheating of individual motors.

When using the Shadow Hand the patient has to be very careful in physical therapy when doing exercises. The right pressure is required, the movements have to be smooth and the actuation needs to be safe. In order for an electronic or robotic device to help the therapist, it needs the same kind of care. Safety is of the upmost importance whenever a robot comes into direct contact with people. The muscle technology makes the hand soft, compliant and human-friendly thus the Hand's technology will be extremely useful in rehabilitation and assistive devices. In order to regulate the pressure and forces applied to the hand, the hand is equipped with a Smart Motor unit. This motor contains an integrated force sensor used to precisely control applied forces. The hand also contains a Hall Effect sensor and rotary magnet as mentioned above. This is accurate to about 1/3 of a degree and provides 34 sensing regions on each finger.

The smart motors implement PID control of force and position of the joints (Shadow Robot Company 2009). The controller calculates and then initiates a corrective action that can adjust the process accordingly and rapidly, to keep the error minimal. This control is flexible and accurate when judging target data. These controllers can be configured via the robot interface. In addition to the onboard controls the Hand can also be controlled by a normal PC running The Shadow Hand Control code.

Smart Hand

Smart Hand (Figure 11) is a prosthetic hand developed by researchers in Sweden and Italy over the last ten years. Smart Hand is a complex prosthesis with four motors and forty sensors designed to provide realistic motion and sense to the user. Smart Hand is comparable to the I-Limb which is another prosthetics hand that is controlled by nerves. Unlike the I-limb, Smart Hand is the first device of its kind to send signals back to the wearer, allowing them to feel what they touch(Saenz 2009). It is able to recreate human level touch interaction, by attaching the prosthetic hand to the patient's nerve endings.

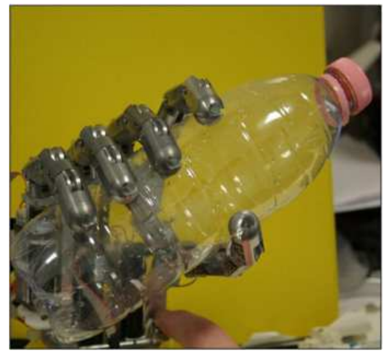

Figure 11: Smart Hand (http://www.greenprophet.com)

The Smart Hand is one of the first of its kind to utilize haptic technology to send signals back to the user to simulate feeling with the bionic limb. “Haptic technology, or haptics, is a tactile feedback technology which takes advantage of a user's sense of touch by applying forces, vibrations, and/or motions upon the user” (Saenz 2009). The idea behind it is similar to that of the I-LIMB, to make this replacement as much like a normal human hand as possible. The developers of the Smart Hand not only want to mimic the full range of functionality of the human hand, but its ability to feel and sense objects.

Since in many cases, an amputee’s brain still remains open to sending and receiving impulses from the nerves of the lost limb, scientists are trying to use electronic sensors to receive these control signals from the nerves and forward them to a mechanical device (singularityhub.com). By means of a surgical procedure a doctor can attempt to attach these sensors in the Smart Hand to the nerves at the point of amputation, giving the patient the ability to not only control the prosthetic hand, but feel with it. With their current prototype, the patient is able to control and feel with the Smart Hand, but it is limited in its current stage due to the lack of sensory feedback.

The goal of the Smart Hand project is to create a replacement limb that is as near to identical to the lost one as possible. The prosthesis will function and relay sensory output like a normal biological hand. Four motors provided full range of motion to the fingers, and slight forward and backward wrist motion. The system consists of a microprocessor, electrodes and a telemetry system implanted in the wearer´s lower arm. The microprocessor receives electrochemical impulses from the central nervous system which translates the electrical messages, converts them to analog/digital information, amplifies the signal and sends the data to the hand which then carries out the specific command. This sophisticated microprocessor allows the user to individually move each finger and perform hand movements up to 15 degrees of freedom such as rotating the wrist and thumb while a human hand can perform movements of 27 degrees of freedom (Saenz 2009).

Smart Hand is unique because it also takes advantage of those phantom limb pathways still being open. Doctors connect the sensors in the hand to the nerves in the stump of the arm. Now, patients can feel as well as control an artificial limb. The Smart Hand project is the work primarily of Lund University in Sweden and the Scuola Superiore Sant'Anna in Italy. However, multiple researchers in Denmark, Israel, Ireland, and Iceland have invested work and resources into this project.

Bionic Arms

The prosthetic arm, which has remained relatively static in form and functionality since the Civil War, has seen major engineering advancements since the advent of the Iraq War. By April of 2008 there were 1.9 million people living in America without one or more limbs. Thirty percent of these amputees had suffered from arm loss. This includes 257,100 amputee Veterans (701 from the Iraq/Afghani War alone) living in the US today. It is also approximated that there are 50,000 new amputations each year (Creg, Neri 2008). Amputation is one of the most severe mental and physical debilitations; it leaves its victims with both mental and physical scars. This is why a successful completion and implementation of a prosthetic arm is not a standard treatment and rehabilitation procedure. The rehabilitation procedure is often focused in re-incorporating and facilitating the patients return to a normal life style. Over the years scientists and engineers have strived to develop fully functional prosthetic limbs.

The research for improving functional prostheses was initiated by the Defense Advance Projects Research Agency (DARPA) after the realization of the inefficiency of prosthetics during the beginning of the Iraq war. DARPA launched the Revolutionizing Prosthetics program in 2005; with this program DARPA began a 50 million dollar project to create two new prosthetic arms. The first arm is funded by a 30.4 million dollar contract that was completed in 2009. That project, led by John Hopkins Applied Physics Laboratory, is attempting to create a fully functional prosthetic arm that is both cosmetically and functionally appealing. This project gave fruits to what is now known as the PROTO Arm. The second arm was completed in 2007. DEKA Research and Development Company developed the prosthetic arm with an 18.1 million dollar contract; this arm was named after the prosthetic worn by Luke Skywalker, the Luke arm (Creg, Neri 2008).

Luke Arm

The Luke Arm (Figure 12) is a robotic arm which is currently going through clinical trials; the arm was designed in the shape and size a human arm, while maintaining a weight under 3.6 kg. The first version of the arm had a control system that acts like a foot-operated joystick; in order to maneuver the arm the users must shift pressure to different parts of a shoe embedded with an array of sensors. If the user presses down with the left big toe, it causes the arm to move out, and pushing down with the right big toe causes the arm to retract. The arm also has a way to provide feedback to the user. To accomplish this, the arm uses a tactor, which is a small vibrating motor about the size of a bite size candy bar, the tactor is secured against the user's skin and vibrates at different speeds depending on the grip strength, which is measured by sensors connected to a microprocessor. When the grip strength is large, the tactor vibrates at a high frequency; when the grip strength is small, it vibrates only slightly. A second version of the Luke arm uses targeted reinnervation, invented by Dr. Todd Kuiken, which attaches to a person's nerves and decodes signals that the nerves send. Now, all a person has to do is think about a movement, this thought will send signals to the nerve, and then the arm will move accordingly.

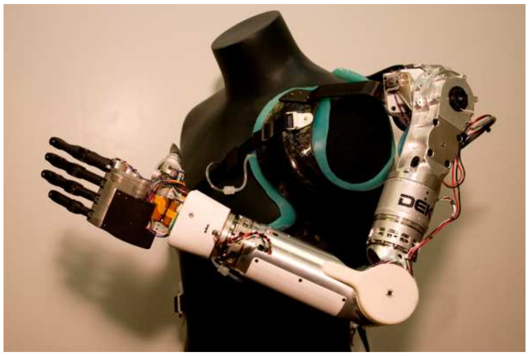

Figure 12 Luke Arm (http://www.wildphotographs.com)

The arm is currently undergoing clinical trials. The study marks the first large-scale testing of the arm, which allows those who have lost a limb up to their shoulder joint to perform movements while reaching over their head, a previously impossible maneuver for people with a prosthetic arm. The study is under the direction of Dr. Linda Resnik at the Providence, R.I., VA Medical Center. Veterans fitted with the arm will provide feedback to guide engineers in refining the prototype, before it is commercialized and also made available through the VA health care system. DEKA is currently researching for a cost-effective way to produce the arm. They hope that the arm will cost around $100,000, which is almost double the cost of the advanced prosthesis.

Proto-1 and Proto-2

The Johns Hopkins University Applied Physics Laboratory (APL) in Laurel, Md., has developed a prototype of the first fully integrated prosthetic arm that can be can be naturally controlled by the nerve system through the use of reinnervation. This arm also provides sensory feedback and allows for eight degrees of freedom. This high level of control and mobility are due to the method developed entitled Targeted Muscle Reinnervation (TMR); this process transfers residual nerve fibers in unused muscles to a different region of the body. For Proto 1 (Figure 13), these are transferred to the patient's chest (Daniels 2009).

Clinical testing of Proto 1 shows an amazing amount of control for functional hand movements. Some of these tests are included removing of a credit card from a pocket, switching thumb position for different grips, and stacking cups. In contrast to virtually every other technique available, the Proto 1 allows the user to have an incredibly high level of control while receiving feedback. The device can provide any number of feedback sensations, one of these sensations is to directly feel the gripping strength of the prosthetic when holding an item. At the moment APL is continuing their research in order to develop Proto 2; this arm will be more sophisticated and should provide 25 degrees of freedom (Daniels 2009).

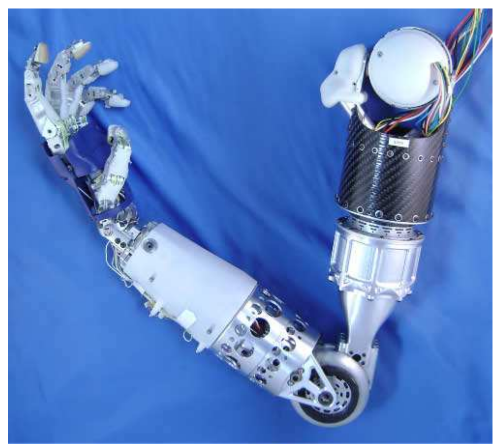

Figure 13 Proto Arm (http://michaelbelfiore.com)

The Proto 2 is still 7 pounds which is two pounds heavier than the ideal weight. The Proto 2 is set to be powered by a hydrogen-peroxide pneumatic system to replace electric motors used in Proto 1 which were bulky, slow and weak. The hydrogen peroxide reacts with an iridium catalyst to drive the arm's movements. The wearer would need to install a fresh hydrogen-peroxide canister each morning. Michael Goldfarb from Vanderbilt University has been developing these hydrogen peroxide cartridges. He hopes to overcome the limitations of electrically powered activation with a novel monopropellant system. When a user plugs a fresh hydrogen peroxide cartridge into his arm a small bursts of mono- propellant would drive the fingers and other articulated joints of the arm by reacting with a catalyst to release steam. Goldfarb envisions that the cooled steam would seep through pores in the arm's cosmesis much like natural sweat in the skin. These cartridges could also be marketed as power sources for commercially available prosthetics if the reactants can be created in a cost-efficient manner (Creg, Neri 2008).

Full Body Exoskeleton

Hybrid Assistive Limb

Hybrid Assistive Limb otherwise known as HAL is a full-body suit designed to aid people who have degenerated muscles or those paralyzed by brain or spinal injuries. This suit can aid the wearer in daily activities such as standing up from a chair, walking, climbing up and down stairs, moving heavy objects. HAL-5 is expected to be applied in various fields such as rehabilitation support and physical training support in medical field, heavy labor support at factories, and rescue support at disaster sites, as well as in the entertainment field. HAL-5 can operate indoors and outdoors but is recommended indoor use until better batteries allow more prolonged use. HAL-5 is being developed by Prof. Sankai and his laboratory at University of

Tsukuba of Japan. Cyberdyne Inc. has been manufacturing and is currently distributing of the HAL-5 to the residences of Japan and a separate office has been setup for distribution in Europe. The exoskeleton is currently valued at $60,000 (*CYBERDYNE Inc.,* 2009).

HAL-5's structure consists of a frame made of nickel molybdenum and an aluminum alloy. Further strengthened by a plastic casing, the metal frame is strapped to the body and supports the wearer externally. Several electric motors act as the suit's muscles to provide powered assistance to the wearer's limbs (*CYBERDYNE Inc.,* 2009). The total weight of the HAL-5 suit is 23kg (about 51 lbs) but the wearer doesn't feel any weight as the suit can support its own weight. HAL-5's upper-body system helps users lift up to 40 kg more than they normally could (Figure 14). Wearing the suit, a healthy adult male can lift 80 kg; roughly double what he can normally. HAL-5 can multiply the overall original strength of the wearer by a factor of 2 to 10. The suit is powered by both nickel-metal hydride and lithium battery packs; a full charge lasts for 2 hours and 40 minutes, with both the upper- and lower-body parts in action.

Figure 14 HAL-5 lifting a 40kg gallon ((http://obychnogo.net)

HAL-5 has a small pouch attached to a belt on the suit that contains a computer that controls it and a Wi-Fi communications system (*CYBERDYNE Inc.* 2009). Two control systems work together to command HAL-5's limbs. The first one, the Bio-Cybernic system, monitors electrical currents known as electromyogram, or EMG. The job of the second control system is to let the wearer and suit move together more smoothly. The first time a person uses the suit it begins memorizing that persons walking patterns. This allows the exoskeleton to match each wearer's distinct gait, which is useful if the person has one leg less capable than the other. It also allows certain people with disabilities whose EMG signals are very faint to use the suit.

The Bio-Cybernic system reads the electrical signals produced by the muscles. When someone performs a physical activity, even as simple as bending a finger, the muscles release a small amount of electrical energy. The Bio-Cybernic system analyzes this change in electrical current and activates the motors when and to what amount of power the user intends to generate. This system also measures the speed at which the user intends to move. For example, when walking, the muscles don't act or (send electrical signals) as fast as they would for someone who is running or kicking, even though most of those same muscles are being used for both activities. The Bio-Cybernic system reads these signals along muscle fibers when a person intends to move by sensors attached to the wearer's skin.

Evaluation

Criteria

From the research gathered it is easy to see that the field of rehabilitation robotics is quite vast, even when narrowed down and focused on specific types of devices. In order to analyze these devices at a more useful level, and make meaningful projections as to the future of some of these technologies used, they need to be broken down into smaller categories and each looked at more closely. These categories and how they are interconnected with each other are shown in Figure 15. This figure shows that the cost is affected by all other categories, in the same way Accessibility is affected by both Training and Adaptability. Based on the research done, observations, and current and past trends witnessed in the field, a list was created that should be sufficient for rating and comparing these devices. Each device will be analyzed within each of the categories and then rated with a value from one to five. The goal of all this is to have some way of looking at all these devices on the same plane, and the categories are as follows:

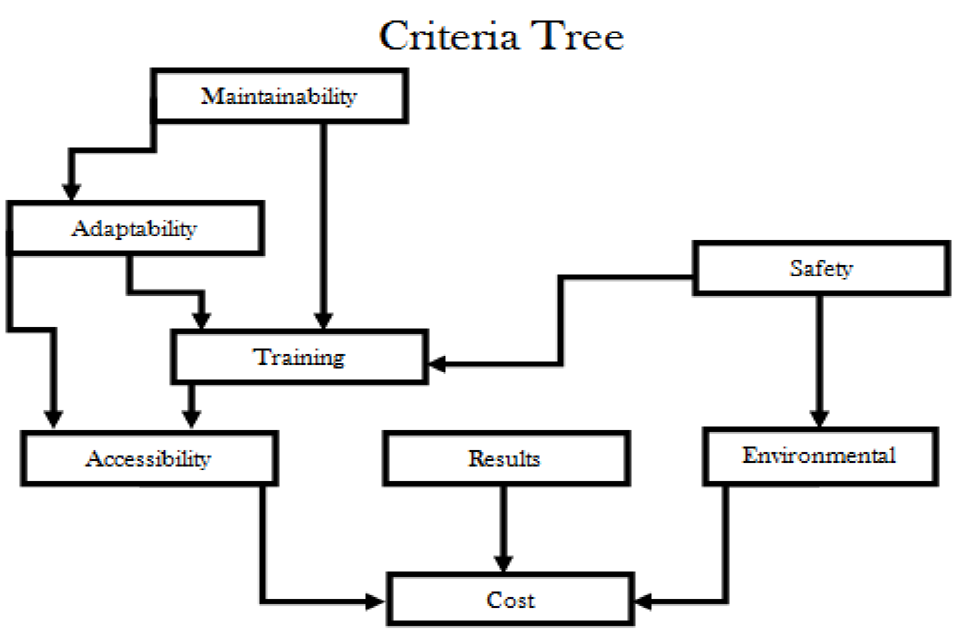

Figure 15: Criteria Tree: This tree shows how our criteria are linked to one another. The cost is affected by all of the other criteria this is because everything plays a role in determining the cost. To read this tree it is as simple as following the arrows decent. Each category has lines below it connecting to the category they affect.

Cost

One of the main criteria is cost. The value of the device in question will depend greatly on its cost because this has an effect on how wide spread an audience this device can potentially reach. This category will help identify whether the device is only attainable by say large rehabilitation centers, or by normal average everyday people. Cost can be the deciding factor for many people depending on the service provider. The reason behind this is that depending on how much the primary care provider makes in a year will determine how much aid the patient will receive from their Health Care Service. An example of this is Medicare which is composed of two programs. The first program, for which most people do not have to pay, covers inpatient and outpatient hospitalization, home healthcare, nursing home care, and hospice care. If you receive prosthesis through one of these providers, the facility will often bill and receive payment directly from Medicare. The second program pays for professional, suppliers of medical devices and equipment, and certain outpatient services. If you receive prosthetic care outside of a facility setting, your prosthesis' will bill Medicare for you but you will pay a monthly fee. This monthly fee will again depend on the yearly income (Medline Plus).

For this category we will be analyzing many aspects other than just the final price tag. Some of the aspects which affect this criterion are maintainability, materials, training, safety, results, etc. which all play a role in determining a devices cost score. The biggest being the results which include how the device helps improve the patients' quality of life. The cost rating a device receives will also be affected by third party payers. Third party payers such as Medicaid, Medicare, health insurance, etc. which will help alleviate the cost to the user thorough one of their programs. In general a low score will be given to devices found to be unaffordable and/or unreasonable and a high score to devices that are cheap and affordable.

Cost Rating	
1	Above $50,000 or no market price available currently
2	$20,000-$50,000 with the help of third party payers
3	$20,000-$50,000 without help of third party payers
4	Under $20,000 with the help of third party payers
5	Under $20,000 without help of third party payers

Table 1: Cost Rating

Accessibility

Some rehabilitation devices can only used in large rehabilitation centers, due to the high costs, large size, maintenance required, or trained personal needed for its operation. But not a lot of areas have such facilities. On top of that some centers don't have or support certain devices, so patients have to travel specific locations to gain access to a device. So how useful a device is can really be limited to the number of patients, who need the device and who actually have access to it. A device that is usable at ones house, everyday, without trained personnel has the possibility of being usable by all who can benefit from it. But of course other things come into play when talking about accessibility, such as results, cost, and safety, to name a few. So to determine an accessibility rating for each device the main factor is the devices range of use. A rating of one will be given to devices limited to large special rehabilitation centers, and a rating of five will correspond with devices usable at home.

Accessibility Rating	
1	Available in limited locations (only in a few States in large facilities)
2	Available in large rehabilitation centers only
3	Available in major hospitals and/or large cities
4	Available in standard rehabilitation centers or hospitals
5	Can be used at home

Table 2: Ratings for Accessibility

Maintainability

Repair costs, power issues, usable outdoors, calibrations, etc. this category covers all of this and more. Clients won't want to use anything that will be malfunctioning all the time and requiring constant maintenance. The device becomes more trouble than it is actually worth, and a lot more costly. Some clients expect to be able to use their device during normal daily life activities, so weather and power issues come into play. Also accessibility for repairs and maintenance become an issue, a person doesn't want to, or in some cases they can't, go weeks without said device while they wait on repairs or a replacement. All of this will be taken into account when determining a devices maintainability score. A rating of one will be given to devices requiring constant maintenance, only usable indoors, and having multiple other issues. A rating of five will be given to devices that require little to no maintenance, usable indoors and outside, and quick and easy access to repairs.

Maintainability Rating	
1	Requires monthly maintenance
2	Requires quarterly maintenance
3	Low maintenance, once or twice a year
4	Requires little maintenance, maybe once a year
5	The device requires little maintenance, some of which can be done by the user.

Table 3: Ratings for Maintainability

Training

This category will investigate the level of training necessary in order for a device to be used properly. Some devices require trained personnel that not only add to the cost, but limit the accessibility of the device. Whereas some devices require none or very little training that the user can pick up on their own. This category looks into these issues because they can affect multiple other categories such as cost and accessibility. Ratings of one will be given to devices requiring professionally trained personnel to use the device, and a rating of five will be given to devices requiring little to no training to operate the device.

Training Ratings	
1	Requires professionally trained personnel all the time to use the device
2	Requires personnel with basic training for constant use
3	Requires professionally trained personnel only for initial use
4	Requires personnel with basic training for initial use
5	No training personnel required

Adaptability

Another issue that needs to be considered is adaptability, is a device adaptable to multiple people, or designed very specifically for the person. Other concerns are whether or not it can be used in a range of environments, more specifically for children, and whether or not the device can adapt to a growing child. After a certain period of time the consumer may contact a physician or rehabilitation professional if there are changes in disability or ability levels. Patients who are newly disabled or in need of new prostheses, will often start the process by consulting with medical and rehabilitation professional before selecting an assistive device. Adaptability of the device is often looked at because it can show how limited a device actually is, and ultimately can have an effect on the cost. A device that is specifically designed to a person will cost more than a device designed for any user. A rating of one will correspond with devices designed for a specific person and a rating of five is given to devices designed for any or all who may need the device.

Adaptability Rating	
1	Designed only for a specific person, no adaptability.
2	
3	Designed only for a specific group, adaptable for people meeting a specific criterion.
4	
5	Adaptable for use by all or most users.

Safety

How safe a device is for users, weight, material, reliability, etc. all play a role in determining this category. This category will look into how safe each device is for a user and those nearby. Many aspects will be taken into account to determine a devices safety rating, from the strain put on the user, to materials used to manufacture the device. Also the interface between the device and the user will be looked at because human error can't be overlooked when looking at safety. In the table below the word malfunction is used to describe when the device is not working in its intended manor, potentially harmful manor. Ratings of one will be given to devices prone to malfunction and error, dangerous devices that put heavy strain on the user. A rating of five is given to devices that put little or no strain on the user, and rarely malfunctions.

Safety Rating	
1	Device with large strain on body, risk of danger to those nearby, serious malfunctions occur occasionally
2	Device with little unmanageable, strain on body, malfunctions occasionally
3	Device with manageable, little strain on body, non-serious malfunctions occasionally
4	Device with minor or unnoticeable strain on the body and malfunctions rarely
5	Device puts no strain on the body and malfunctions rarely and nothing life threatening

Table 4: Safety Ratings

Environmental Concerns

Mainly this category looks at the construction and disposal of the device as well as the materials used. This category will determine if the device is environmentally friendly or not, in terms of its construction and its disposal. The reusability of a device will also be taken into account since that is a form of recycling. In general a rating of one will be given to non recyclable devices that are harmful to the environment, and a five is given to devices that can be recycled or reused, and cause little to no harm to the environment.

Environmental Concerns Rating	
1	Non recyclable parts and harmful to the environment
2	
3	Some recyclable parts and little to no harm to the environment
4	
3	Recyclable parts and no harm to the environment

Table 5: Environmental Concerns Rating

Results

This category looks at the results gained by using a certain device. Some of the aspects that will be taken into account when determining this score will be how long the clients must use the device before positive results can be seen, what it takes to maintain the results and the likelihood of patients relapsing. Patient relapse is basically the patient losing the gained results and ending up back where they started. This is a very important category because it shows how well a device actually works, how it will be rated is shown in the following table.

Results Rating	
1	Results take a year or longer, high chance of relapse, continuous use needed to maintain results
2	Results after a year, likely chance of relapse, continuous use needed to maintain results
3	Results in under a year, low chance of relapse, daily routine or exercise needed to maintain results
4	Results in a few months, relapses are rare, weekly routine/exercise needed to maintain results
5	Immediate results, no chance of relapse, little or no steps needed to maintain results

Table 6: Results Rating

Analysis

In this section explanations will be given as to how these data was analyzed to evaluate each of our devices. Multiple charts were used to derive and show different steps in our group's analysis of the devices. The following charts also explain the process used to evaluate the rating system shown above.

The Pair-Wise Comparison Chart (Table 8) matches each category with each other category to determine whether it is of equal, greater, or lower value than that of the other category which it is currently being compared with. Each and every category gets matched up with all of the others to determine an order of importance amongst the categories. Then the total values are added up for each category. Finally these totals help to determine the weights that each category is assigned.

	Cost	Accessibility	Maintainability	Training	Adaptability	Safety	Environmental Concerns	Results	Total
Cost	0	1	1	1	1	0.5	1	0.5	6
Accessibility	0	0	0.5	1	0	0	1	0	2.5
Maintainability	0	0.5	0	0.5	1	0	1	0	3
Training	0	0	0.5	0	0.5	0	1	0	2
Adaptability	0	1	0	0.5	0	0	1	0	2.5
Safety	0.5	1	1	1	1	0	1	0	5.5
Environmental Concerns	0	0	0	0	0	0	0	0	0
Results	1	1	1	1	1	1	1	0	7
0	Less Value								
0.5	Equal Value								
1	Greater Value								

Table 7: Pair Wise Comparison Chart

After the order of importance has been determined each category will be assigned proper weights. To do this we added four to each of the scores calculated in the pair-wise comparison and then divided that by four. This was done to make sure each category's score was greater than four. Essentially this was done to attain a weight between one and three (Table 9).

Category	Pair-Wise Score	Shift up 4	Scale by a factor of 4
Results	7	11	2.75
Cost	6	10	2.50
Safety	5.5	9.5	2.38
Maintainability	3	7	1.75
Accessibility	2.5	6.5	1.63
Adaptability	2.5	6.5	1.63
Training	2	6	1.50
Environmental Concerns	0	4	1.00

Table 8: Weights Chart

Now that the categories have been weighted the scores were tallied up. This process is shown in Table 10. To do this each category was assigned possible ratings, and then the maximum rating it could receive was taken and multiplied with that categories weight. This provided the maximum weighted score for each category and it was then rounded, anything greater than or equal to .5 was rounded up, and rounded down for anything below .5. These were then all added together and this provides a maximum possible score of 76.

Category	Pair-Wise Score	Rating	Max Rating	Weight	Max Weighted Score
Cost	6	1 to 5	5	2.5	12.5
Accessibility	2.5	1 to 5	5	1.63	8.13
Maintainability	3	1 to 5	5	1.75	8.75
Training	2	1 to 5	5	1.5	7.50
Adaptability	2.5	1 to 5	5	1.63	8.13
Safety	5.5	1 to 5	5	2.38	11.9
Environmental Concerns	0	1 to 5	5	1	50.0
Results	7	1 to 5	5	2.75	13.8
Total (rounded)					76.0

Table 9: Maximum Weight

Table 11 shows each of the devices discussed in our paper rated and scored using the ratings described in the criteria section of the paper, and its weighted score. How this table was arrived at has been displayed and described in the preceding tables. The scores each device is given one based on an open discussion amongst the members of the group, discussing the scores each device should receive in each category, based on the research gathered and trends observed. After a bit of discussion a score was reached and recorded in the table.

	Weight	BLEEX	LOPES	HAL-5	I-Limb	Shadow Hand	Smart Hand	Luke Arm	Proto Arms
Cost	2.5	1	1	3	5	1	1	1	1
Accessibility	1.63	4	3	5	5	1	5	2	2
Maintainability	1.75	2	2	2	4	2	3	1	1
Training	1.5	3	1	3	3	3	3	3	3
Adaptability	1.63	3	4	4	5	5	5	4	5
Safety	2.38	3	4	4	5	5	5	5	5
Environmental Concerns	1	3	3	3	3	3	3	3	3
Results	2.75	5	1	5	5	5	5	5	5
Weighted Score		45.8	34.1	56.4	68.9	48.9	57.1	47.1	48.8
Total		46	34	56	69	49	57	47	49

Table 10: Final Ratings

Based on the previous evaluations it was possible to derive a means by which these devices could be compared side by side as well as create a basis for future projections to be made. From the overall scores from the evaluation it can be seen that the I-LIMB scores higher than all the other devices. The I-LIMB is a small bionic hand with individually motorized fingers that allow a person to replace their lost hand with a bionic one that mimics many normal functionalities of a normal hand. Based on the research gathered the I-LIMB's projected success can be attributed to many factors such as its production, functionality, cost, etc.

However these devices fall under different categories, exoskeletons, bionic hands, and bionic arms. To keep things accurate these devices should not be compared to devices from other categories. Despite the I-LIMB having the highest score, the BLEEX rates number one for exoskeletons and it's a tie for the bionic arms.

Bionic Hands

The I-LIMB's overall cost is about $18,000. Although the price is relatively high it received a higher Cost rating due to the price of the Shadow Hand which is estimated cost of $100,000, for relatively the same effects.

Accessibility is another category where the I-LIMB set itself apart primarily from the Shadow Hand. The I-LIMB and the Smart Hand both received a score of 5 in accessibility because the I-LIMB is currently accessible to various patients, and it is usable at home and in normal day to day activities. When it comes to Accessibility the Smart Hand is not currently available on the market, but will be available for everyday life. The Shadow Hand got a low score of 1because it is primarily used when dealing in specialized circumstances, such as environments that are not human friendly.

The only other place where the I-LIMB differs in terms of score is maintainability. The I-LIMB received a score of 4; this is because of the reliability of the device and the fact that it is enclosed in a protective cosmesis skin to shield it from the environment. The Smart Hand received a 3, the main difference between the two devices is the higher level of complexity of the Smart Hand. However like the I-LIMB the Smart Hand can be enclosed in a protective cosmesis skin to shield it from the environment. The Shadow Hand received a score of 2 and this is due to it utilizing 40 pneumatic tubes in its design. Because of the use of these 40 pneumatic tubes it will need to be inspected and maintained regularly to keep it functioning properly. Also due to the environments in which the Shadow Hand was developed to be used in, regular maintenance will be required.

Aside from these differences the devices scored the same in every other category. The reason for this is their similar designs and overall functions. Each of the devices meets and performs their desired results and these devices are relatively safe for the users. Due to these facts each device was given an equal score for the remaining categories.

Bionic Arms

The bionic arms that have been examined are the Luke Arm and the Proto Arm. It wasn't until the war in Iraq that prosthetic arms got a major overhaul. DARPA began a 50 million dollar project to create two new prosthetic arms. An 18.1 million dollar contract went toward the development of the Luke Arm and 30.4 million dollar contract toward the development of the Proto Arm. The reason for their development was to give returning soldiers with amputations a chance to pursue a normal life. The fact that these two arms were fund by DARPA and developed for the same reason makes these two arms very similar.

The Luke Arm and Proto Arm score the same in almost all aspects as determined in Table 11. The Luke Arm and Proto Arm score a 48 and 50 respectively. Both received a score of 1 in the cost for the fact they both cost the same amount of $100,000. For accessibility and maintainability they score the same also, because both are only available in a limited location and do not require a lot of maintenance. Originally the Luke Arm was controlled by a sensor in the feet, now both are controlled by nerves and direct signals from the brain. These two arms are similar in nearly every other way.

However, these two arms do differ in a few aspects. The two arms are look differently and are progressing differently. The Proto Arm will receive a new look, similar to the I-Limb, the proto Arm will be made to more closely resemble a human arm in terms of looking like human skin. The Proto Arm is still under development while the Luke Arm is already in testing.

Exoskeletons

For this project three exoskeletons were analyzed, the BLEEX, the LOPES and the HAL 5. Although each exoskeleton was designed for a specific function they all share similar traits. The BLEEX was designed to allow first responders and soldiers to carry heavy for longer periods of time. When carrying these loads the user will only feel a fraction of the weight. The HAL 5 was designed for two purposes; the first is to augment the strength of the user. The second purpose is to be used as a walking aid for those who could use a bit of extra power, such as person with disabilities or anyone who needs to carry a large load. The final exoskeleton is the LOPES. The LOPES is a lower extremity rehabilitation exoskeleton, its only purpose is to aid in gait rehabilitation.

When comparing these exoskeletons we noticed that within the criteria these exoskeletons had very similar results. When rating the Accessibility of these devices the facilities and their operations were taken into consideration. The BLEEX received an Accessibility rating of four. The four is due to the fact that once this unit is finalized it should be available to most soldiers or first responders. In this same category the HAL-5 was rated with a five for Accessibility. The Hal-5 received a five for two reasons, the first reason being that the exoskeleton has been designed to be used in any facility. The second reason being that it is available for rent at $600 per month (MedGaget, 2007); this means that anyone can rent this exoskeleton and use it at home. In this same category the LOPES is rated at a three since it is being designed for use in large rehabilitation centers.

In the maintainability section each of these devices received a rating of two. The reason behind these ratings is that exoskeletons require at the minimum quarterly maintenance in order to assure their functionality and safety. For the training category the Hal-5 and BLEEX received a rating of three. This value is due to the fact that a user will require initial training in order to use the exoskeletons. The LOPES received a one for this category. The LOPES receives a one since the user will required a physician present at all times.

When it comes to Adaptability and Safety the HAL-5 and LOPES scored a four on both criteria. The Hal-5 can be designed for people with different body types while the LOPES can be used by anyone in need of gait rehabilitation. When it comes to safety the HAL-5 has been designed to support its own weight, this means that it doesn’t apply any additional forces on the human body. For the LOPES the user will require a physician present at all times, this will reduce the risk of damage to the human body. BLEEX scored a three on both sections, the exoskeleton has been designed for adults in a specific field, and due to this it obtains a three for adaptability. When it comes to safety the BLEEX receives a three since the exoskeleton is powered by a hybrid engine which requires gasoline. This added factor reduced the safety of the exoskeleton to three.

When it comes to the result criteria the HAL-5 and BLEEX both received a five. This five means that both systems are functioning as they were designed, they meet their objectives. Contrary to them the LOPES received a one for result. The reason behind this rating is that LOPES does not meet its objective. After executing some tests engineers discovered that walking in LOPES does not significantly change muscle activation (EMG) measurements during walking.

The final criteria to be analyzed is cost, cost is one of the most important criteria in our report since it holds a heavy weight in our analysis. When it came to comparing the cost of these devices the BLEEX and the LOPES both scored a one while the Hal 5 scored a three. The LOPES and BLEEX both received a one since there isn't an official price for these units. Depending of the official price of the BLEEX the overall rating for our evaluation might change.

At the moment HAL-5 is the highest rated exoskeleton, this means that according to our current rating the HAL-5 has the highest possibility of becoming a commercial success. This overall rating might change once the official prices of the BLEEX or LOPES exoskeleton are announced. At the moment are projection of the commercial success seems to be correct. The HAL-5 is currently producing 400 units annually at a price of $42,273.

Projections

In the previous section of this report our analysis showed that the I-Limb has the best possibility of becoming a commercial success. Even though this might be true the technology applied to each of the devices mentioned in this report will affect the field of Rehabilitation Robotics. This technology has paved the path for a bright future in this field. For the next part of our report we will analyzing the possible ways that the technology applied in this devices can impact our future.

BLEEX and LOPES

The BLEEX and LOPES exoskeletons use metal leg braces which are powered motors to make it easier for the wearer to walk. BLEEX contains sensors and actuators in the device which are used to provide feedback information to adjust the movements and the load while walking. The device's controller and engine are located in a vest attached to a backpack frame. While the device itself weighs 100 pounds, it enables a person to haul a 70-pound backpack, while feeling as if he/she is merely carrying 5 pounds. The LOPES exoskeleton has been designed to help the user with gait rehabilitation. These are two examples of very similar exoskeletons which have been created for different purposes.

In case of the BLEEX exoskeleton, it has been design as a military exoskeleton but it can also be used by civilians. If this technology is fully developed it can become a bio-mechatronic device. Bio-mechatronic devices are devices aims to integrate mechanical elements, electronics and parts of biological organisms. When fully developed the bio-mechatronic devices can provide improved motor functions which can mimic normal biological functions to impaired individuals. Similar to the LOPES they can be used to train individuals with impaired motor functions as well as enhance the performance of normal individuals.

BLEEX being one of the first autonomous exoskeletons has opened the door for a future in which exoskeletons will be part of everyday life. As the technology advances it is possible to find ways to build exoskeletons at a price which will one day be affordable for the general population. The same thing can be said for the development of power sources which will allow a system similar to the BLEEX to function for a 8 hour period or longer. With this being the case, in 10 to 15 years you might catch a person strapped to an exoskeleton bringing home the groceries, going for a stroll in the park or you find yourself carrying a watching machine across the room.

Bionic Limbs

When we hear the word "bionics" most people immediately think of Luke Skywalker from Star Wars or the Bionic Women. No more than 10 years ago these characters where part of a world of pure science fiction, but now days we are slowly turning them into reality. This is being achieved with the development of bionic limbs like the Proto and Luke Arm. There is no doubt that the recent prostheses developments are going to help hundreds perhaps thousands of people with serious disabilities to lead a normal life. The question now becomes; how will it affect our future and what effect will it have in our culture?

There are many obstacles which we must keep in mind while making our projections. The main challenges faced by present bionic limbs are power, electromechanical implementation and neural control signals. Out of these obstacles the main concern is related to powering the bionic limbs. At the moment the bionic limbs have been powered with lithium ion batteries. This battery currently allows for the arm to be used for 18-20 hours, after which, the battery must be replaced (Kinne, 2009).

The second obstacle is electromechanical implementation. This refers to replicating the complexity of the entire limb's movements while including actuators, sensors and other components into the look and weight of a human limb. A good example of this are the Luke and Proto arm which replicate the appearance and weight of a human arm but offer less degrees of freedom. The electromechanical implementation refers to maintaining a balance between function and aesthetics.

The third challenge for bionic limbs is the neural control signals. At the moment this challenge has almost been overcome with targeted muscle reinnervation. This is an especially important obstacle to conquer due to the fact that the human arm has seven degrees of freedom, and the hand has more than 20. With 27 degrees of freedom it will be almost impossible to develop a physical controller which will allow us to use all of these degrees of freedom. This fact alone is the reason for which reinnervation might become a standard controller for robotic prosthesis. With these obstacles in mind we are able to create projections for the future of bionic limbs.

It's possible that the artificial limbs such as the Luke Arm and the Proto Arm will become fully functional artificial limb within the next 15 to 20 years. The reason behind this is that there is real and immediate needs for such limbs, and meet the technological requirements to achieve this deadline. It is simply a matter of how soon this technology will be perfected to produce limbs virtually indistinguishable from normal biological ones. Within this time period the procedure to attach these limbs to the human body will have been perfected.

Within 10 years after the Bionic Limbs have been perfected it'll become possible for engineers to create limbs which will exceed the ability of our biological limbs. With the constant improvement in lithium power cells, in 10 years powering these bionic limbs shouldn't be a problem. The technological advancements will also make it possible to build fully functional bionic limbs similar in size and weight to the human limb. The reason behind this will be the fact that bionic limbs will appear to be cooler, stronger, more sensitive, more dexterous, and most importantly not prone to irreparable damage.

With the technological advances there are also social issues that must be reconsidered; some of these are as follow. This will bring up the cultural issue of whether this will be socially acceptable or not. It will also bring up the issue of how it will be regulated. An example of such regulations is the case of Oscar Pistorius, a South African Paralympic runner who participated in the 2007 international able-bodied competitions. Due to his artificial lower legs which enabled him to compete, there were some claims that he has an unfair advantage over able bodied runners. The same year, the International Association of Athletics Federations (IAAF) amended its competition rules to ban the use of any technical device that incorporates springs, wheels or any other element that provides a user with an advantage over another athlete not using such a device. This decision was reversed by the Court of Arbitration for Sport on 16 May 2008 (Science Daily, 2009). Although the decision of the IAAF was amended we still need to consider how bionic limbs will affect our community, which leads us to ask the following questions. Will players with bionic limbs be allowed to participate in professional sports teams or will there be laws to ban the use of bionic limbs from sports? Will a bionic limb make you illegible to enter the military services or will it be recommended for military services? These are some of the questions that must be considered as we move into a new age where bionic limbs will become part of everyday life.

Hal-5

Hybrid Assistive Limb otherwise known as HAL is a full-body suit designed to aid people who have degenerated muscles or those paralyzed by brain or spinal injuries. Hal-5 will be very useful in the field of rehabilitation robotics. The suit allows the wearer to become very strong and able to lift very heavy objects. Thus the HAL-5 can be applied in many fields from like as simple to helping warehouse workers move crates to helping fire fighters move debris. One idea in mind for the suit will be in aiding nurses move patients.

As mentioned above the HAL-5 has two control systems that work together to command HAL-5’s limbs. The Bio-Cybernic system monitors electric currents known as electromyogram signals on the wearer's body. The other control system is to let the wearer and suit move together more smoothly. The first time a person uses the suit it begins memorizing that persons walking patterns. This allows the exoskeleton matches each wearer's distinct gait, which is useful if the person has one leg less capable than the other. It also allows certain people with disabilities, whose EMG signals are very faint to use the suit. These two systems will give certain people a chance to perform simple and basic activities as if they didn't have a disability. People that are losing muscle strength will no longer have to be confined to the limits of their body and will be able to continue their regular life.

The Bio-Cybernic system will be useful for many new devices in the further development of rehabilitation robotics. By using the Bio-Cybernic system a prostheses can record and read electromyograms and act accordingly to the signals. A weak person would now be able to perform the toughest of tasks with the help of such a device. It would also be helpful in retraining people to use muscles that have been affected by degenerative diseases.

The Hal-5 can be considered a real version of an Iron man suit. This exoskeleton has been designed for rehabilitation purposes but it can also be tuned with military capabilities. The suit not only increases the strength of the pilot but it also makes traveling easier. In the future one of the main hiking equipment will be an exoskeleton device and soldiers will be seen marching in a Hal suit.

Conclusion

The field of rehabilitation robotics is ever expanding. New research is leading to the creation of new devices and technologies each year. Some devices that have been analyzed here show the direction in which the field is heading. Several devices were evaluated including lower extremity exoskeletons like BLEEX and LOPES; bionic limbs such as I-Limb, Shadow Hand and Smart Hand; bionic arms like Luke Arm and Proto-1 and Proto-2; and the full body exoskeleton Hybrid Assistive Limb. After evaluating all the devices, certain aspects became prevalent as being key components for the success of a device. Devices such as the I-Limb, shows great potential in being accessible to everyone with good results both in cost and maintainability. I-Limb costs $18,000, which is relatively low compared to the other devices. With the help of third-party payers, the user would not be burdened with the total cost. I-Limb is also a relatively simple device; the wearer only has to get it attached and they're done. The I-Limb would not burden the wearer with constant maintenance.

Other devices like the Smart Hand and Proto Arm, incorporates more of the human aspects of sensory feedback, allowing the wearer to actually feel what they are interacting with. With the inclusion of sensory feedback people will be able to receive signals from nerves that were once cut off. Sensory feedback also helps the wearer become more accepting of their device. One of the most alienating aspects of getting an artificial arm is accepting it as a permanent limb. Sensory feedback will help break the barrier between man and machine. The HAL-5 and the Shadow Hand are composed of even more complex subsystems such as EMGs and PID controllers, in order to more closely simulate a human-like performance. These devices can replicate human performance near perfectly. The HAL-5 can allow stroke victims to regain a lot of control that they lost. The Shadow Hand uses the PID controller to perfectly mimic a human hand for every action, including how the hand moves and the amount of pressure the hand can exert over an object.

The technologies that make these devices possible have opened the door to a new world of possibilities. People will be able to regain the functions that they have lost with the help of rehabilitation robotics.

Works Cited

"Amputation Statistics by Cause Limb Loss in the United States." *National Limb Information Center*. 2008. Web. 3 Dec 2009.
<http://136.142.82.187/eng12/history/spring2008/finAl/8077.pdf>.

Bogue, 2009, R. "Exoskeletons and Robotic Prosthetics: A Review of Recent Developments." Industrial Robot: An International Journal, 36 (2009) 421-427.

Daniels, Tom. "THE DEVELOPMENT OF BRAIN-MACHINE INTERFACING FOR THE RESTORATION OF FUNCTION." (2009)
< http://136.142.82.187/eng12/history/spring2009/pdf/9151.pdf >

Dollar, A. M., and H. Herr. "Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art." IEEE transactions on robotics: a publication of the IEEE Robotics and Automation Society 24.1 (2008): 1-15.

Ekkelenkamp, R., J. Veneman, and H van der Kooij. "IEEE International Conference on Robotics and Automation." *LOPES: a lower extremity powered exoskeleton*. (2007)

Highfield, Roger. "Revolutionary bionic arm unveiled." *Telegraph* 2 May 2007

"Hybrid Assistive Limb." *CYBERDYNE Inc.*. 2009. CYBERDYNE Inc., Web. 9 Nov 2009.
<http://www.cyberdyne.jp/English/robotsuithal/index.html>.

Kazarooni, H. "Exoskeletons for Human Power Augmentation." *Proceedings of the 2005 IEEE*. (2005) < http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=01545451 >

Kazarooni, H, Jean-Louis Rasine, and Steager Ryan. "On the Control of the Berkeley Lower Extremity Exoskeleton (BLEEX)." *Proceedings of the 2005 IEEEXplore*. (2005)

Kazarooni, H, Zoss Adam, and Chu Andrew. "On the Biomimetic Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)." *Proceedings of the 2005 IEEEXplore*. (2005)

Kennedy, David. "DEKA's "Luke Arm"." Web. 18 Nov 2009. http://www.ele.uri.edu/courses/ele282/F08/David_1.pdf

Ling, Geoffrey. "Revolutionizing Prosthetics ." *Defense Science Office*. Web. 3 Dec 2009. <http://www.darpa.mil/dso/thrusts/bio/restbio_tech/revprost/index.htm>.

Mraz, Stephen. "Giving soldiers a high-tech leg up ." *Machine Design*. Web. 23 Nov 2009. <http://machinedesign.com/article/giving-soldiers-a-high-tech-leg-up-1208>.

Neri, Thomas, and Jim Cregg. "NEW PROSTHETIC ARMS PROVIDE GREATER QUALITY OF LIFE FOR AMPUTEES." Web. 15 Nov 2009. <http://136.142.82.187/eng12/history/spring2008/finAl/8077.pdf>.

Olsen, Stephanie. "More tech visions of future from NextFest." *Tech Tepublic*. 9-17-07. CNET News, Web. 11 Dec 2009. <http://content.techrepublic.com.com/2346-1035_11-164689.html>.

Saenz, Aaron. " Prosthetic Smart Hand Lets Amputee Feel and Move Objects." *Singularity Hub*. 15 Oct 2009. Singularity Hub, Web. 9 Nov 2009. <http://singularityhub.com/2009/10/21/prosthetic-smart-hand-lets-amputee-feel-and-move-objects/>.

Sofge, Erik. "Popular Mechanics." *DARPA's Better Bionic Arm: Our Most Limb-Like Prosthetic* July 2007 < http://www.popularmechanics.com/science/health_medicine/4218218.html>

"Technical Specification." *Shadow Robot Company*. 15 Aug 2009. Shadow Robot Company Ltd., Web. 9 Nov 2009. <http://www.shadowrobot.com/downloads/shadow_dextrous_hand_technical_specification_C6M.pdf>. <http://www.shadowrobot.com/hand/techspec.shtml>.

Reference

Bar-Cohen, Y. (2004). Electroactive polymer (EAP) actuators as artificial muscles: Reality, potential, and challenges SPIE press. < http://electrochem.cwru.edu/encycl/art-p02-elact-pol.htm>

Bar-Cohen, Y. (2005). Current and future developments in artificial muscles using electroactive polymers. Expert Rev.Med.Devices, 2(6), 731.

Billard, A., & Matarić, M. J. (2001). Learning human arm movements by imitation: Evaluation of a biologically inspired connectionist architecture. Robotics and Autonomous Systems, 37(2-3), 145-160.

Binkley, P. (2003). Predicting the potential of wearable technology. IEEE Engineering in Medicine and Biology Magazine, 22(3), 23-27.

Blaya, J. A. (2002). Force-Controllable Ankle Foot Orthosis (AFO) to Assist Drop Foot Gait,

Bogue, 2009, R. (2009). Exoskeletons and robotic prosthetics: A review of recent developments. Industrial Robot: An International Journal, 36

Burgar, C., Shor, P., Majmundar, M., & Van der Loos, M. (2002). Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. Archives of Physical Medicine and Rehabilitation, 83(7), 952-959.

Carroll, K., & Edelstein, J. E. (2006). Prosthetics and patient management: A comprehensive clinical approach Slack Incorporated.

< http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B7CVK-4MWXTF6-4&_user=74021&_coverDate=12%2F31%2F2007&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1217852261&_rerunOrigin=google&_acct=C

000005878&_version=1&_urlVersion=0&_userid=74021&md5=01cc9e5c885be0708592c40344963752>

Clements, I. P. (2008). How prosthetic limbs work. Retrieved from http://health.howstuffworks.com/prosthetic-limb.htm

Cooper, R. A., Ohnabe, H., & Hobson, D. A. (2007). An introduction to rehabilitation engineering. New York: Taylor & Francis. Retrieved from http://www.loc.gov/catdir/toc/ecip0616/2006021440.html; http://www.loc.gov/catdir/enhancements/fy0661/2006021440-d.html

DELLON, B., & MATSUOKA, Y. Exoskeletons, and rehabilitation.

Dollar, A. M., & Herr, H. (2008). Lower extremity exoskeletons and active orthoses: Challenges and state-of-the-art. IEEE Transactions on Robotics : A Publication of the IEEE Robotics and Automation Society, 24(1), 144.

Egermann, M., Kasten, P., Thomsen, M., Egermann, M., Kasten, P., & Thomsen, M. (2009). Myoelectric hand prostheses in very young children. International Orthopaedics; International Orthopaedics, 33(4), 1101.

Exoskeletons and robotic prosthetics: A review of recent developments.(2009). Industrial Robot; the Industrial Robot, 36(5), 421.

Franceschini, M., Baratta, S., Zampolini, M., Loria, D., & Lotta, S. (1997). Reciprocating gait orthoses: A multicenter study of their use by spinal cord injured patients. Archives of Physical Medicine and Rehabilitation, 78(6), 582-586.

Guizzo, E., & Goldstein, H. (2005). The rise of the body bots [robotic exoskeletons]. IEEE Spectrum, 42(10), 50-56.

Harwin, W., Rahman, T., & Foulds, R. (1995). A review of design issues in rehabilitation robotics with referenceto north american research. IEEE Transactions on Rehabilitation Engineering, 3(1), 3.

Kargov, A., Werner, T., Pylatiuk, C., & Schulz, S. (2007). Development of a miniaturised hydraulic actuation system for artificial hands. Sensors & Actuators: A.Physical,

Kiguchi, K., & Fukuda, T. A 3 DOF exoskeleton for upper limb motion assist: Consideration of the effect of bi-articular muscles. Paper presented at the 2004 IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04, , 3

Lundborg, G., Brnemark, P. -., & Rosén, B. (1996). Osseointegrated thumb prostheses: A concept for fixation of digit prosthetic devices. The Journal of Hand Surgery, 21(2), 216-221. doi:DOI: 10.1016/S0363-5023(96)80103-1

Lünenburger, L., Colombo, G., Riener, R., & Dietz, V. Clinical assessments performed during robotic rehabilitation by the gait training robot lokomat. Paper presented at the International Conference on Rehabilitation Robotics (ICORR), 345–348.

MedGaget <http://medgadget.com/archives/2007/04/lease_an_exoskeleton_in_2008.html>

Medline Plus http://www.nlm.nih.gov/medlineplus/assistivedevices.html#cat49

Moreno, J., Brunetti, F., Pons, J., Baydal, J., & Barbera, R. (2005). Rationale for multiple compensation of muscle weakness walking with a wearable robotic orthosis. Paper presented at the Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on, 1914-1919.

Pons, J., Moreno, J., Brunetti, F., & Rocon, E. Lower-limb wearable exoskeleton.

PRIOR, S., WARNER, P., WHITE, A., PARSONS, J., & GILL, R. (1993). Actuators for rehabilitation robots. Mechatronics; Mechatronics : Mechanics, Electronics, Control, 3(3), 285.

Rosen, J., & Perry, J. C. (2007). Upper limb powered exoskeleton. International Journal of Humanoid Robotics, 4(3), 529.

Smith, L. L. Prosthetic limb development: A historical review. Discussions, , 9.