Final Master Thesis
Master of Artificial Intelligence
Universitat Politecnica de Catalunya

AI and Prosthetics

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Terms of Reference

The objective of this Final Master Thesis is to provide an aggregated detailed bibliographic work where the reader can learn anything concerning the prosthetic limbs. Prosthetic limbs is a very interesting area of Artificial Intelligence, Biomedical Engineering and more fields like Neuroscience. The goal of this Thesis is to show the huge innovations and developments of technology that has inserted the field of the prosthetics. Starting with the history behind, the first prosthetic limbs ever made, continuing with the impact on Artificial Intelligence, meeting Bionic limbs that would actually fully replace a biological limb. The reader will learn about the latest researches that are made on this field surprised by the possibility that a bionic hand would actually substitute the brain-hand communication with a constant feedback information, not merely mimics the movement. Main models that serve the needs of many amputees will be analyzed, in parallel with the cost. Another solution, 3D Printing, which is the latest technology nowadays comes to provide an artificial limb for 800$, resolving the affording problem. I will analyze also models of prosthetic arms costing 49$. The reader will also see from the point of view of the amputee, as much as possible and the problems he is facing after losing a limb and with the new artificial one. Nevertheless, after the importance of the field of prosthetics is analyzed and highlighted, the thesis is finishing with a proposal to the Master Program of Artificial Intelligence held by the University Polytechnic of Catalunya to insert a direction on the teaching program.

Abstract

The topic of prosthetic limbs has opened a new world to those that have lost limbs giving them an option to regain some increased functionality or normalcy. Prosthetic limbs are amazingly important to amputees because a prosthesis can help restore some of the capabilities lost with the amputated limb. Although prosthetic limbs have still not advanced to the point where they can equal the functionality provided by biological limbs, the capabilities they do provide are significant. As we know, bionic limbs is a great field of Artificial Intelligence. The introduction of information technology to prosthetics has allowed bionic limbs to emerge and change the way we were thinking about prosthetic limbs. The ability to easily connect the prosthetic to a person's brain or muscular system for movement has been made simpler by neural signal. We will be even more amazed from the latest technology inserted in bionic prosthetic limbs. With developments in information technology, the way in which bionic limbs are connected to a person can advance. Allowing progression from simple prosthetics that were merely limb replacements to functioning limbs, to ones that can respond similar to a true limb to become less complicated. Great strides are being made each day in the field of prosthetics, and while great technological challenges remain, artificial limbs are becoming increasingly similar to real limbs. There are more and more companies creating new innovative models, according to people's needs. The cost can decrease from the competition, but maybe not enough for everyone. Here comes 3D Printing, a latest development to give solutions with a cost of 800$. Who can afford an Össur's and Ottobock's prosthetic limb? Are there other options? What is the State of the Art of each model? What are the significant differences we have to focus on? All these questions will be answered in a detailed bibliographic work presented. Then the reader would read information about the point of view of the amputee. What are the problems after losing a limb? What is the meaning of the term *phantom limb pain* and what are the consequences on the psychology of the amputee? Nevertheless, after the importance of the field of prosthetics is analyzed and highlighted, the thesis is finishing with a proposal to the Master Program of Artificial Intelligence held by the University Polytechnic of Catalunya to insert a direction on the teaching program for the students that may be interested in this field.

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Acknowledgements

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Last but not least, I would like to thank my parents and friends in Greece for their support and their encouragement to me, the past two years I am leaving and studying in Barcelona.

Aims and Objectives

The main aim of this Master Thesis is to make a review about the field of prosthetic limbs, to examine the historical development, and analyze the state of the art of the prosthetics. More particular, I will try to analyze and refer to the state of the art of 6 prosthetic limbs, knees, feet and arms, of Össur and Otto Bock as also RSL Steeper, that got my interest to analyze further since the introduction of Artificial Intelligence made them extremely interesting and nevertheless are broadly useful to the users improving their everyday life. Furthermore, I will refer to 3D Printing and the innovations on the field of prosthetics, as also to the differences of the technology and the cost comparing to a high level prosthetic limb of a company like Össur or Otto Bock. The point of view of the patient is really important so there will be a reference on the sixth chapter. I will finish with a suggestion to the faculty of the Master in Artificial Intelligence carried at Universitat Politecnica de Catalunya to introduce more courses about prosthetics, and even more add a direction, the students can follow if they wish, since the importance of introducing the subject to this field of studies has certainly an academic interest and there is a possible contribution to the humanity.

The reason I picked this topic, is because the area of prosthetic limbs was the reason I enrolled to this Master. I thought it was the most related one in order to follow this career. Even though the courses were not that much related to prosthetics, I realized that this thesis can be a reason to insert this area to our master as a direction to whom is interested. Also, I believe that prosthetics is a great example how technology can improve people's lives and as an engineer that gives me the courage to continue working and gain more knowledge everyday about innovations and new technologies that can ameliorate our lives. As a graduate student of Biomedical Engineering, this topic is of great interest and a way to integrate the master degree to my previous studies.

1. Introduction

In the first chapter an introduction on prosthetics will be presented, followed by an historical review of prosthetic limbs. Also, I will mention a general state of the art of the prosthetics.

In the second chapter, I will analyze the entrance and the impact of Artificial Intelligence on prosthetic limbs. A general state of the art will be presented, as also there will be a subchapter about Bionic limbs, which is a great example of the development of technology and how it has improved people's lives.

At chapter three, the reader will learn about Hugh Herr and his research program on MIT about BiOM Ankle-Foot Prosthetic device. I will analyze the state of the art and the results of his research.

In the fourth chapter I will introduce Össur and Otto Bock to the readers, two of the main companies that construct artificial limbs. At this chapter, I will analyze the state of the art of 6 main models of lower and high extremity prosthetics, that got my interest, because of the high level of technology inserted, and of course Artificial Intelligence.

The next chapter will introduce 3D Printing to the reader, the state of the art of the prosthetics, and will bring forward some more social issues, like the cost of a prosthetic limb, who can afford to buy a prosthetic from big companies, as well as a necessary comparison of the technology used on 3D printing prosthetics and the ones constructed by a company like Otto Bock.

In the sixth chapter, I will try to discuss about the patient's point of view and how a prosthetic limb can improve his life. Also the issue of social inclusion of these units will be presented.

The seventh chapter is indicating to the Faculty of Universitat Politecnica de Catalunya and more particular to the Master of Artificial Intelligence and the lack of courses related to the Prosthetic limbs. I am openly suggesting to the master coordinators to introduce courses and directions that the student can follow related to this - in my opinion - interesting area.

At the eight chapter are held my conclusions after writing this thesis, as also the optimistic ambitions and expectations for the future.

Last but not least, at the final chapter are written all the helpful references that helped me complete this thesis.

1.1 Prosthetic Limbs

In medicine, a prosthesis (plural: prosthesis; from Ancient Greek "πρόσθεσις" prósthesis) is an artificial device that replaces a missing body part, which may be lost through trauma, disease, or congenital conditions. Prosthetic amputee rehabilitation is primarily coordinated by a prosthetist and an inter-disciplinary team of health care professionals including psychiatrists, surgeons, physical therapists, and occupational therapist,[1] and mostly concerning this thesis, occupations such as engineers, program and software developers and finally the field of biomedicine.

A limb may be amputated or missing because of a blood vessel disorder (such as atherosclerosis or damage due to diabetes), cancer, an injury (as in a motor vehicle crash or during combat), or a birth defect. In the United States, slightly fewer than 0.5% of people have an amputation. However, the percentage is likely to increase in the coming years because of the rising rate of obesity, which increases the risk of atherosclerosis and diabetes.

An entire limb or just part of one may be amputated. A lower-limb amputation may involve a toe, a foot, part of the leg below or above the knee, or an entire leg (at the hip). An amputation may even extend above the hip. An upper-limb amputation may involve one or more fingers, a hand, part of the arm below or above the elbow, or an entire arm (at the shoulder).

If a body part is missing, an artificial device (prosthesis) is often recommended to replace that part. At a minimum, a prosthesis should enable the user to perform daily activities (such as walking, eating, and dressing) independently and comfortably, as well as affordability and personalization. However, a prosthesis may also enable the user to function as well or nearly as well as before the amputation.[2]

1.2 Historical review

1.2.1 History

Prosthetics have been mentioned throughout history. The earliest recorded mention is the warrior queen Vishpala in theRigveda. The Egyptians were early pioneers of the idea, as shown by the wooden toe found on a body from the New Kingdom. Roman bronze crowns have also been found, but their use could have been more aesthetic than medical.

An early mention of a prosthetic comes from the Greek historian Herodotus, who tells the story of Hegesistratus, a Greekdiviner who cut off his own foot to escape his Spartan captors and replaced it with a wooden one.

[1] https://en.wikipedia.org/wiki/Prosthesis
[2] http://www.merckmanuals.com/home/special-subjects/limb-prosthetics/overview-of-limb-prosthetics

1.2.2 Wood and metal hands

A famous and quite refined historical prosthetic arm was that of Götz von Berlichingen, made at the beginning of the 16th century. The first confirmed use of a prosthetic device, however, is from 950-710 B.C.E. In 2000, research pathologists discovered a mummy from this period buried in the Egyptian necropolis near ancient Thebes that possessed an artificial big toe. This toe, consisting of wood and leather, exhibited evidence of use. When reproduced by bio-mechanical engineers in 2011, researchers discovered that this ancient prosthetic enabled its wearer to walk both barefoot and in Egyptian style sandals. Previously, the earliest discovered prosthetic was an artificial leg from Capua.

Around the same time, François de la Noue is also reported to have had an iron hand, as is, in the 17th Century, René-Robert Cavalier de la Salle. During the Middle Ages, prosthetic remained quite basic in form. Debilitated knights would be fitted with prosthetics so they could hold up a shield, grasp a lance or a sword, or stabilize a mounted warrior. Only the wealthy could afford anything that would assist in daily life.[citation needed] During the Renaissance, prosthetics developed with the use of iron, steel, copper, and wood. Functional prosthetics began to make an appearance in the 1500s.[3]

Artificial iron hand believed to date from 1560–1600

[3] Friedman, Lawrence (1978). The Psychological Rehabilitation of the Amputee. Springfield, IL.: Charles C. Thomas.

1.2.3 Technology progress before the 20th century

An Italian surgeon recorded the existence of an amputee who had an arm that allowed him to remove his hat, open his purse, and sign his name. Improvement in amputation surgery and prosthetic design came at the hands of Ambroise Paré. Among his inventions was an above-knee device that was a kneeling peg leg and foot prosthesis with a fixed position, adjustable harness, and knee lock control. The functionality of his advancements showed how future prosthetics could develop.

Other major improvements before the modern era:

- Pieter Verduyn – First non-locking below-knee (BK) prosthesis.
- James Potts – Prosthesis made of a wooden shank and socket, a steel knee joint and an articulated foot that was controlled by catgut tendons from the knee to the ankle. Came to be known as “Anglesey Leg” or “Selpho Leg”.
- Sir James Syme – A new method of ankle amputation that did not involve amputating at the thigh.
- Benjamin Palmer – Improved upon the Selpho leg. Added an anterior spring and concealed tendons to simulate natural-looking movement.
- Dubois Parmlee – Created prosthetic with a suction socket, polycentric knee, and multi-articulated foot.
- Marcel Desoutter & Charles Desoutter – First aluminium prosthesis
- Henry Heather Bigg, and his son Henry Robert Heather Bigg, won the Queen’s command to provide "surgical appliances" to wounded soldiers after Crimea War. They developed arms that allowed a double arm amputee to crochet, and a hand that felt natural to others based on ivory, felt, and leather.

1.2.4 Modern methods

Lower-limb prosthetics

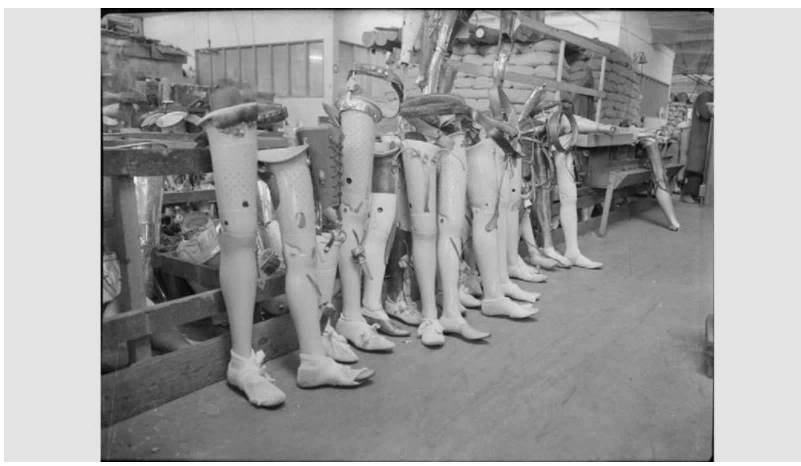
For the first time, artificial limbs were being mass-produced in response to the enormous number of casualties in World War One. In the US, the Walter Reed Army Hospital produced a large number of artificial limbs for the returning veterans. This example is of a welding attachment and other tools integrated into the limbs for amputees to return to work after the war..

The technology continued to develop after WW1. DW Dorrance invented the split hook artificial hand shortly before World War I. It became popular with labourers after the war who were able to return to work using the attachment because of its ability to grip and manipulate objects. It’s one of the few designs that have remained relatively unchanged over the past century. Dorrance demonstrated its multi-functionality in the 1930s by driving a car using the arm.

In the UK, Queen Mary's Hospital, Roehampton, became a centre for manufacturing artificial limbs in the World War Two. It opened in 1939. In its first year, 10,987 war pensioners attended the centre, with an additional 16,251 limbs being sent by post. At the outbreak of war, the factory was expanded because of the realization that 40,000 UK servicemen had lost limbs in WW1.

However in WW2 there was around half the number of amputees. As Leon Gillis, QMH Consultant Surgeon from 1943-1967, observed, advances in surgical techniques, treatment of infections and the availability of blood transfusion after WW1 all reduced the need for amputation.[4]

At the end of World War II, the NAS (National Academy of Sciences) began to advocate better research and development of prosthetics. Through government funding, a research and development program was developed within the Army, Navy, Air Force, and the Veterans Administration.[5]



Queen Mary's Hospital, Roehampton became an important centre for manufacturing limbs

Upper-limb prosthetics

The practice of upper-limb prosthetics is much different than that for the lower limb. There is often a lot of customizing, adjusting, tweaking, problem-solving, and trial and error. Done right, it requires more time and can be frustrating. Patients unhappy with the fit or function of their prosthesis will likely just not wear it. They don't "need" to after all; they have another hand. However, a large percentage of patients end up with overuse injuries of their sound arm. And, of course, there are many things it is helpful to have 2 "hands" for. People with bilateral amputations (both sides) who rely on their prosthetic arms exclusively would especially benefit from working with a practitioner with

[4] http://www.bbc.com/future/story/20151030-the-geniuses-who-invented-prosthetic-limbs
[5] "A Brief History of Prosthetics". inMotion: A Brief History of Prosthetics. November–December 2007. Retrieved 23 November 2010.

extensive experience. It may also be that such practitioners are more familiar with and adept at dealing with insurance companies with regard to obtaining authorization and coverage for upper-limb prostheses. In addition, the use of myoelectrics is extremely complicated and unique. There are specialized computer programs, electrodes, microprocessors, and wires that must be connected correctly, programmed, and maintained. Many practitioners unfamiliar with the technology may be reluctant to attempt it and rather go with what they know--the standard body-powered hook--, even though it may not be the best choice for that particular patient.

It is difficult to figure out who to go to for upper-limb prosthetic care. Within the field, there are professional organizations for practitioners interested in that area, but that information is not readily available to prospective patients.[6]

Upper-limb prosthetics

1.2.5 Robotic prosthesis

Robots can be used to generate objective measures of patient's impairment and therapy outcome, assist in diagnosis, customize therapies based on patient's motor abilities, and assure compliance with treatment regimens and maintain patient's records. It is shown in many studies that there is a significant improvement in upper limb motor function after stroke using robotics for upper limb rehabilitation.[7] In order for a robotic prosthetic limb to work, it must have several components to integrate it into the body's function: Biosensors detect signals from the user's nervous or muscular systems. It then relays this information to a controller located inside the device, and processes feedback from the limb and actuator (e.g., position, force) and sends it to the controller. Examples include surface electrodes that detect electrical activity on the skin, needle electrodes implanted in muscle, or solid-

[6] http://www.upperlimbprosthetics.info
[7] Reinkensmeyer David J (2009). "Robotic Assistance For Upper Extremity Training After Stroke". Studies In Health Technology And Informatics 145: 25–39.

state electrode arrays with nerves growing through them. One type of these biosensors are employed in myoelectric prosthesis.

A device known as the controller is connected to the user's nerve and muscular systems and the device itself. It sends intention commands from the user to the actuators of the device, and interprets feedback from the mechanical and biosensors to the user. The controller is also responsible for the monitoring and control of the movements of the device.

An actuator mimics the actions of a muscle in producing force and movement. Examples include a motor that aids or replaces original muscle tissue.

Targeted muscle reinnervation (TMR) is a technique in which motor nerves, which previously controlled muscles on an amputated limb, are surgically rerouted such that they reinnervate a small region of a large, intact muscle, such as the pectoralis major. As a result, when a patient thinks about moving the thumb of his missing hand, a small area of muscle on his chest will contract instead. By placing sensors over the reinervated muscle, these contractions can be made to control movement of an appropriate part of the robotic prosthesis.[8] [9]

A variant of this technique is called targeted sensory reinnervation (TSR). This procedure is similar to TMR, except that sensory nerves are surgically rerouted to skin on the chest, rather than motor nerves rerouted to muscle. Recently, robotic limbs have improved in their ability to take signals from the human brain and translate those signals into motion in the artificial limb. DARPA, the Pentagon's research division, is working to make even more advancements in this area. Their desire is to create an artificial limb that ties directly into the nervous system.[10] We will analyze further the Robotic prosthetics in the following chapters.

1.2.5.1 Robotic lower-limb prosthetics

Lower-limb amputees tend to expend more energy and walk more slowly than individuals with intact joints, and also develop compensatory mechanisms for walking and other activities which increase the demand on their intact joints and muscles, leading to long-term musckuloskeletal health problems. Recent advancements in the requisite technology have facilitated the emergence of prostheses capable of generating power comparable to that generated by the intact limb for many activities of daily living.

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[8] Kuiken TA, Miller LA, Lipschutz RD, Lock BA, Stubblefield K, Marasco PD, Zhou P, Dumanian GA (February 3, 2007). "Targeted reinnervation for enhanced prosthetic arm function in a woman with a proximal amputation: a case study". Lancet 369(9559): 371–80. doi:10.1016/S0140-6736(07)60193-7. PMID 17276777

[9] "Blogs: TR Editors' blog: Patients Test an Advanced Prosthetic Arm". Technology Review. 2009-02-10. Retrieved 2010-10-03.

[10] "Defense Sciences Office". Darpa.mil. Retrieved 2010-10-03.

1.2.5.2 Robotic upper-limb prosthetics

Advancements in the processors used in myoelectric arms has allowed developers to make gains in fine tuned control of the prosthetic. The Boston Digital Arm is a recent artificial limb that has taken advantage of these more advanced processors. The arm allows movement in five axes and allows the arm to be programmed for a more customized feel. Recently the i-Limb hand, invented in Edinburgh, Scotland, by David Gow has become the first commercially available hand prosthesis with five individually powered digits. The hand also possesses a manually rotatable thumb which is operated passively by the user and allows the hand to grip in precision, power and key grip modes.

Another neural prosthetic is Johns Hopkins University Applied Physics Laboratory Proto 1. Besides the Proto 1, the university also finished the Proto 2 in 2010. Early in 2013, Max Ortiz Catalan and Rickard Brånemark of the Chalmers University of Technology, and Sahlgrenska University Hospital in Sweden, succeeded in making the first robotic arm which is mind-controlled and can be permanently attached to the body (using osseointegration[i]).[11] [12] [13]

An approach that is very useful is called arm rotation which is common for unilateral amputees which is an amputation, that affects only one side of the body; and also essential for bilateral amputees, a person who is missing or has had amputated either both arms or legs, to perform tasks of daily living. This involves inserting a small permanent magnet into the distal end of the residual bone of subjects with upper limb amputations. When a subject rotates the residual arm, the magnet will rotate with the residual bone, causing a change in magnetic field distribution.[14] EEG signals which is electroencephalogram, a test that detects electrical activity in the brain using small flat metal discs attached to your scalp, essentially decoding human brain activity used for physical movement, are used to control the robotic limbs. This is very essential being that it provides a more lively affect to the robotic limb, giving oneself control over the part as if it was their own.[15]

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[11] World Premiere of Muscle and Nerve Controlled Arm Prosthesis.

[12] Permanently attached robotic arm, operated on mind-control.

[13] Max Ortiz Catalan and his robotic arm.

[14] Li Guanglin, Kuiken Todd A (2008). "Modeling of Prosthetic Limb Rotation Control by Sensing Rotation of Residual Arm Bone". IEEE transactions on bio-medical engineering 55 (9): 2134–2142. doi:10.1109/tbme.2008.923914

[15] *Contreras-Vidal José L.; et al. (2012). "Restoration of Whole Body Movement: Toward a Noninvasive Brain-Machine Interface System". Ieee Pulse 3 (1): 34–37.*doi:10.1109/mpul.2011.2175635

1.3 Statistics

Before getting deeper on prosthetics, it is interesting to view some statistics about world's amputees and realize that the field of Prosthetics concerns more people that we would imagine. Worldwide prevalence estimates of amputation is difficult to obtain, mainly because amputation receives very little attention and resources in countries where survival is low. Therefore, we can get statistics, unfortunately mainly about the U.S.A, European countries and some exceptions of developing countries like Haiti.

Nevertheless, the World Health Organization estimates that in Latin America, Africa, and Asia combined, almost 30 million people require prosthetic limbs, braces, or other devices, up from 24 million in 2006.

1.3.1 Numbers and percents on amputations

U.S.A

- 50,000 new lower limb amputations every year in USA based on information from National Center for Health Statistics
- ratio of upper limb to lower limb amputation is 1:4
- most common is partial hand amputation with loss of 1 or more fingers, 61,000
- next common is loss of one arm, 25,000
- existence of 350,000 persons with amputations in USA, 30% have upper limb loss
- of this, wrist and hand amputations are estimated to make up 10% of upper limb population
- transradial amputations make up 60% of total wrist and hand amputations
- which means 70% of all persons with upper limb amputations have amputations distal to the elbow(3)
- In US 41,000 persons are registered who had an amputation of hand or complete arm
- 60% of arm amputations are between ages 21 and 64 years and 10% are under 21 years of age

There are more than 1,700,000 people in the United States living with limb loss. Every year, more than 130,000 people in the United States undergo amputation of a limb.[16] The United States has a higher lower limb amputation rate compared to other developed countries. The Marshall Islands have been identified to also have a very high rate of lower limb amputation, by world standards. From 1991-2000, rates of diabetes related to lower extremity amputations decreased in The Netherlands.

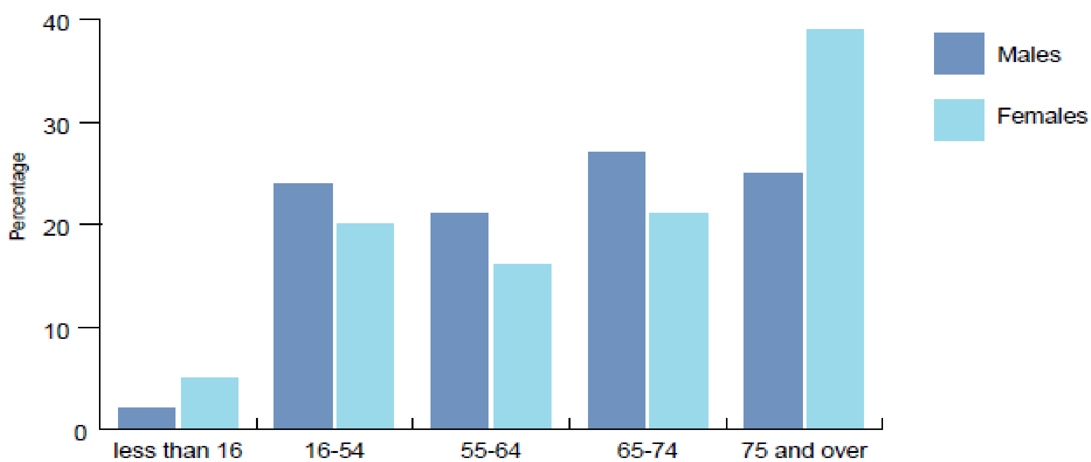
[16] Insurance Fairness for Amputees Act of 2011, S. 773, 112th Cong. (2011).

In a World Health Organization multinational study of vascular disease in diabetes, the results showed that the incidence of lower limb amputation was higher in the American Indian centers than in the East Asian centers . Moreover, the earthquake that shook Haiti in 2010 ranks among the largest ever loss of limbs in a single natural disaster. The overall rates of amputation due to trauma or malignancy are decreasing while the incidence of dysvascular amputations is rising.

Limb loss can be the result of trauma, malignancy, disease, or congenital anomaly. Vascular disease is the most common cause of limb loss overall, with the rate of dysvascular amputation being nearly 8 times greater than the rate of trauma related amputations, the second leading cause of limb loss. Diabetes mellitus is also present in almost half of all cases, and people with diabetes mellitus have a 10 times higher risk of . Cancer related amputations are a rare cause for lower limb amputation.

UK

An interesting statistics table is the following, which highlights the difference in age at presentation between males and females, with females tending to be older for the years 2004/2005 referring to the UK. Almost 40 per cent of female referrals occur within the 75 and over age group whilst this age group accounts for around one quarter of males. By contrast, almost half of all male referrals were aged less than 65 compared with 40 per cent of females.



Percentage of new referrals by age and gender : 2004/05

The table below presents data on the number of upper and lower limb amputations carried out in hospitals within the United Kingdom during 2004/05. The total number of primary amputations in the United Kingdom has increased this year from 16,699 in 2003/04 to 17,039. The most common level of amputation within the UK is amputation of the leg at 37 per cent. This rate varies within the four countries with leg amputations in Scotland accounting for 45 per cent and 28 per cent in Northern Ireland.[17]

Operation	England	Scotland	Wales	Northern Ireland	Total
Amputation of Arm	98	18	11	5	132
Amputation of Hand	3249	400	320	163	4132
Amputation of Leg	4 958	803	344	122	6 227
Amputation of Foot	663	49	23	17	752
Amputation of Toe	4 886	509	269	132	5 796

UK Upper and Lower Primary Amputations : 2004/05

1.3.2 Causes leading to amputation

Reasons for amputation include cardiovascular disease, traumatic accidents, infection, tumors, nerve injury (trophic ulceration), and congenital anomalies. Most frequent causes of upper limb amputation are trauma and cancer, followed by vascular complications of disease right arm more frequently involved in work related injuries.[18] Congenital upper limb deficiency has an incidence of approximately 4.1 per 10000 live births.

Congenital	8.9%
Tumor	8.2%
Disease	5.8%
Trauma	77%

Causes of Upper Extremity Amputation (in percent)

[17] The Amputee Statistical Database for the United Kingdom 2004/05.
[18] http://biomed.brown.edu/Courses/BI108/BI108_2003_Groups/Hand_Prosthetics/stats.html

1.3.3 Hand injuries and occupational accidents - Statistics and prevention

- Hand injuries count for a 1/3 of all injuries at work, 1/3 of chronic injuries, 1/4 of lost working time, 1/5 of permanent disability.
- This varies from activity to activity and with the material element involved.
- An average of 22 working days are lost, but this varies according to lesion.[19]

We have to mention that according to the Digest of Data on Person with Disabilitities, more than 3 million people in the USA have a disability in their hands and/or forearms, including paralyzations, orthopedic impairments, either congenital or injury related.[20]

About one in every 2000 new born babies will have some form of a limb deficiency; it may be absent parts of fingers or toes, complete absence of all four limbs or something in between. Another larger group of children lose limbs in accidents, especially to lawn mowers, trains, all terrain vehicles, and motorcycles; or to disease, including cancer.[21]

Also, according to the *LIMBS FOR LIFE FOUNDATION*:

"Every week 2,996 people lose a limb."

A survey regarding extremity amputations & mental health issues conducted by Ron VanDerNoord, MD of the Frazier Rehab Center in cooperation with the Amputee Coalition of America provides the following insight into amputee rehabilitation:

- "75% of amputees said they needed more education than they were given from their medical professionals."

- "57% of amputees said they received NO educational materials."

- "Of the 43% who did receive materials, only 15-20% of the available materials were considered helpful."[22]

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[19] *Centre de Controle medical des accidents du travail, Paris.*
[20] USA 1983-1986, from the Digest of Data on Person with Disabilitities, U.S. Department of Education, prepared January 1992
[21] "Faces of Adoption," "National Adoption Center," website
[22] http://www.aboutonehandtyping.com

2. AI and Prosthetics

2.1 Evolution

Because technology has improved so much in the last decade, much more functional and comfortable prosthesis are available. Nowadays, we can positively enjoy and take advantage of technological developments, in order to improve our lives where destiny or fate decides for us. In many cases, the introduction of the prosthesis to the patient, manages to bring life in previous conditions, even more give the patient a chance for new experiences and definitely a different way of thinking the meaning of life. Highly motivated and otherwise healthy people with a prosthesis can accomplish many extraordinary feats. For example, some go skydiving, climb mountains, run marathons, complete triathlons, participate fully in sports, or return to demanding jobs or to active duty in the military. They are living life without limitations. And whether a person uses a prosthesis only for activities at home or for a marathon, the prosthesis can provide profound psychologic benefits.

How well a prosthesis enables the user to function depends on his or her anatomy and several other factors:

- Fit, stability, and comfort of the prosthesis
- Socket type and components selected
- User's goals, overall health, age, and frame of mind

Success is most likely when a clinical team (doctor, prosthetist, physical therapist, rehabilitation counselor) work with the amputee to determine the best possible fit and the most appropriate type of prosthesis. The prosthetist is an expert who designs, fits, builds, and adjusts prosthesis and provides advice about how to use them. A user who is motivated will increase the likelihood of long-term success.[23]

[23] http://www.merckmanuals.com/home/special-subjects/limb-prosthetics/

2.2 When AI first was inserted

The Intelligent Prosthesis was first commercially available microprocessor controlled prosthetic knee. It was released by Chas. A. Blatchford & Sons, Ltd., of Great Britain, in 1993 and made walking with the prosthesis feel and look more natural. An improved version was released in 1995 by the name Intelligent Prosthesis Plus.[24] Blatchford released another prosthesis, the Adaptive Prosthesis, in 1998. The Adaptive Prosthesis utilized hydraulic controls, pneumatic controls, and a microprocessor to provide the amputee with a gait that was more responsive to changes in walking speed. Cost analysis reveals that a sophisticated above-knee prosthesis will be about $1 million in 45 years, given only annual cost of living adjustments.[25]

2.3 General state of the art

2.3.1 Components of the prosthesis

Components are the working parts of the prosthesis. They include terminal devices (artificial fingers, hands, feet, and toes) and joints (wrists, elbows, hips, and knees), as well as metal or carbon fiber shafts, which function as bones.

Components that are controlled by microprocessors and powered myoelectrically are replacing the older hydraulic, body-powered models. Myoelectric prosthesis create movement using the electrical charges naturally produced when a muscle contracts. The electrical charges are sent to an electric motor that moves the limb. These new components are more efficient and cause less stress to users.

Bionic components, which are just now becoming available, may enable people to function even better. Bionic components are moved as if by thinking, similarly to natural limbs. Such movement is made possible by rerouting the nerves that once went to the amputated limb and connecting them to healthy muscle in the body (for example, to chest muscle for an amputated arm). These nerves direct impulses once sent to the amputated limb through electrodes on the skin’s surface to microprocessors in the prosthetic limb and thus enable the user to move the limb.[26]

[24] “Blatchford Company History”, Blatchford Group
[25] Pike, Alvin (May/June 1999). "The New High Tech Prostheses". InMotion Magazine 9
[26] http://www.merckmanuals.com/home/special-subjects/limb-prosthetics/prosthetic-parts

2.3.2 Options

The prosthetist explains the available options and helps people choose the type of prosthesis and the options they need to accomplish their goals. For example, women who want to be able to wear shoes with different heel heights may prefer a prosthetic ankle that can adjust to different heights. People who swim can get a second prosthetic leg that is designed for swimming and can withstand water, salt, and sand. Runners can get prosthetic feet specifically designed for running.

2.4 Prosthetic lower limb types

Prosthetic knee systems are among the most complex of all components. This is because knees must give support when people stand, allow smooth motion when people walk, and permit movement when people sit, bend or kneel. We will focus on Prosthetic knees analysis on this thesis, in order to show how important AI is at this field. Prosthetic knees range from simple systems that have been used for hundreds of years to advanced computer-based systems that are popular today. While the perfect prosthetic knee has yet to be invented, research shows great promise with many new types of technology.Today, there are over 100 types of knee systems to choose from. Doctors, prosthetists and rehabilitation specialists consider an amputee's age, health, activity level, and lifestyle when making suggestions about which types of knees and their options for stability and motion control would work best for them.

There are two major types of knees — *mechanical* and *computerized*. Each type has advantages (what works well) and disadvantages (what doesn't work as well).

2.4.1 Mechanical Knees

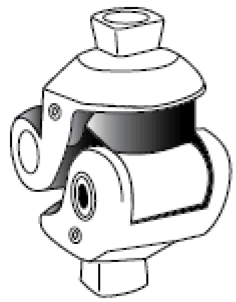
Mechanical knees can be divided into two types: *single-axis* and *polycentric* (more than one axis).

Single-axis knee

This type of knee works like a simple hinge. It:

- is durable (lasts a long time)
- is lightweight
- costs less than other knee systems
- has no stance control, which means that amputees must use their own muscles to remain stable when standing

- often uses a manual lock to compensate for lack of stance control
- often uses friction to keep the leg from swinging forward too fast when moving to the next step.

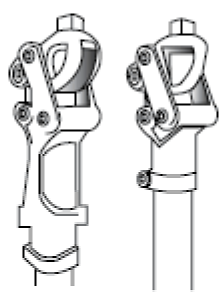


Single-axis knee

Polycentric knee

This type of knee is more complex, allowing more freedom of motion. It also:

- may need to be repaired or replaced more often than other types of prosthetic knees
- weighs more than single-axis knees
- is very stable during early stance phase (at the beginning of a step)
- reduces the leg's length when beginning a step, lowering the risk of stumbling
- bends in the swing phase (when one leg is in the air) or when the user sits down
- works well for many amputees, including those who have had problems with other prosthetic knees or have knee disarticulation, bilateral leg amputations, or long residual limbs
- has a simple swing control that allows for an ideal walking speed
- often has a fluid swing control (a piston inside a cylinder containing air or oil) to allow different walking speeds
- may restrict some knee motion, but not enough to be a problem.



Polycentric knee

Stability Options

There are two types of stability options for mechanical knees — manual locking knees and weight-activated stance-control knees.

Manual locking knee

This type of knee:

- is the most stable knee available
- automatically locks in extension to prevent buckling
- can be unlocked easily
- takes a lot of energy and causes a stiff, awkward gait when the knee is locked
- can be used by amputees who are weak or unstable as well as those who are more active but walk on uneven ground.

Weight-activated stance-control knee

This type of knee:

- is very stable
- applies constant friction to the axis during leg swing
- will not bend when a person's weight is on the prosthesis
- is often an amputee's first prosthesis or used by those who are older or less active.

Motion Control Options

All knee systems need some type of swing control to keep a steady gait. There are two options — constant friction and variable friction motion control.

Constant friction

These systems:

- are simple
- are lightweight
- are dependable
- can only be adjusted to one walking speed at a time.

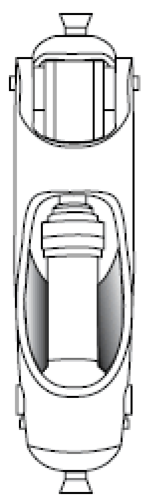
Variable friction

These systems:

- give increased resistance as the knee bends from full extension
- allow variable walking speeds
- need frequent adjustment and replacement of moving parts
- perform similarly to fluid control systems but are considered less advanced in design.

Fluid Control Systems

Fluid control systems work like pistons to provide varying degrees of resistance during swing phase, allowing amputees to walk comfortably at different speeds. There are two types of fluid control systems — pneumatic (using air) and hydraulic (using fluid).



Fluid Control Systems

Pneumatic control

These systems:

- compress air as the knee is flexed, storing energy, then returning energy as the knee moves into extension
- can have a spring coil to add more gait control
- provide better swing control than friction systems
- are less effective than hydraulic systems.

Hydraulic control

These systems:

- use liquid (usually silicone oil) to respond to a wide range of walking speeds
- provide nearly normal knee function
- are heavier, need more maintenance, and cost more than pneumatic systems
- are often used by active amputees.

2.4.2 Computerized (Microprocessor) Knees

Computerized knees are relatively new types of prosthetic technology. There are several types now available, and others are in development. Although each model has slightly different features and performance characteristics, all computerized knees:

- are usually smaller and more lightweight than mechanical knees
- are initially programmed to “learn” the user’s walking characteristics
- have timing, force, and swing sensors that take readings 50 times per second or faster, and instantly adjust the fluid control system accordingly
- take less effort to control timing, which means that amputees have a more natural gait, longer walking endurance, and better control on uneven surfaces, even when going down stairs
- are appropriate for moderately to very active amputees.[27]

[27] http://www.amputee-coalition.org/easyread/military-instep/knees-ez.html

2.4.3 Foot Prosthesis

Options for foot prosthesis include:

- Solid ankle, cushioned heel
- Single-axis design
- Multiple-axis (multiaxial) design
- Stored-energy (dynamic response) design
- Sport-specific

2.4.4 Solid ankle, cushioned heel (SACH) foot prosthesis

This type of prosthesis consists of a basic immovable foot made of rubber and wood. Stability is provided for the knee when the heel touches the ground because its soft heel allows the whole foot to contact the ground. However, less stability is provided when the person raises the heel and the opposite leg swings forward, resulting in uneven walking. A SACH prosthesis requires more energy to use than other types of prosthetic feet. It is appropriate for people who are limited in their activities and is not a good choice for active people.

2.4.5 Foot prosthesis with single-axis design

A prosthesis with single-axis design has an ankle joint that allows the foot to flex up or down. This design allows the whole foot to quickly contact the ground after the heel touches the ground and for the knee to straighten quickly. Because of these features, the prosthesis provides good stability for the knee, which is particularly important for people with above-the-knee amputation. Single-axis design prosthesis are not appropriate for active people.

2.4.6 Foot prosthesis with multiple-axis (multiaxial) design

A foot prosthesis with multiaxial design has an ankle joint that allows the foot to flex up or down and for the ankle to rotate or move to face inward or outward. This design enables users to walk on uneven terrain more easily and is thus appropriate for active people. With newer, lightweight models, minimal maintenance is required. The prosthesis can be made to look lifelike.

2.4.7 Foot prosthesis with stored-energy (dynamic response) design

A foot prosthesis with stored-energy design is made of carbon graphite, which is lightweight and strong. It requires less energy to use because the foot stores energy from when the heel touches the ground to when the toes push off, propelling the person forward. The design may include a shock absorber to reduce the force of contact with the ground during walking. A person who uses this type of prosthesis is able to walk smoothly and relatively naturally. This type of foot prosthesis is appropriate for active people.

2.4.8 Sport-specific foot prosthesis

Foot prosthesis can be customized for a specific sport. For example, for runners (long-distance and sprinting), the prosthesis is designed with the foot bent downward toward the sole and with the capacity to store energy needed to propel the person forward. For swimmers, the prosthesis is designed with an ankle that allows full range of motion in water.

2.4.9 Knee Prosthesis

Options for knee prosthesis include:

- Single-axis, constant friction design
- Polycentric design
- Weight-activated stance control feature
- Manual lock feature
- Fluid control system
- Microprocessor feature

2.4.10 Knee prosthesis with single-axis, constant friction design

A prosthetic knee with single-axis, constant friction design has only one pivot point (the knee bends like a hinge). The design is simple, and the prosthesis is durable, lightweight, and inexpensive. The prosthesis uses friction that does not vary to control the leg when it swings forward. People can walk normally at only one speed. The prosthesis relies on correct alignment by the prosthetist and muscle control by the user to provide stability.

2.4.11 Knee prosthesis with polycentric design

This type of knee prosthesis has several hinges with several pivot points that change as the knee moves, providing increased stability. The prosthesis shortens slightly when the knee is bent, so that the toe clears the ground more easily when the leg swings forward. The polycentric design of this type of prosthesis provides stability for people with a short residual limb and is also appropriate for people whose leg has been amputated at the knee joint, enabling users to sit more comfortably without the knee protruding.

2.4.12 Knee prosthesis with weight-activated stance control feature

A prosthesis with weight-activated stance control feature locks the knee in a slightly bent position (to provide braking) when weight is put on the foot. Constant friction is used to control the leg when it swings forward, but the prosthesis has a knee extension aid, which helps swing the leg. A person who uses this type of prosthesis can walk at only one speed. The prosthesis is appropriate for people with weak muscles.

2.4.13 Knee prosthesis with manual lock feature

A knee prosthesis with manual lock feature can be locked or unlocked by users as needed but requires a cable to do so. Although this type of prosthesis provides the most stability, it requires more energy to use than other types of prosthetic knees. Because the prosthesis has somewhat limited movement during walking, walking is stiff and awkward, making this the least desirable choice.

2.4.14 Knee prosthesis with fluid control system

Knee prosthesis with fluid control system may use compressed air (a pneumatic system) or fluid (an hydraulic system) to produce, store, and release energy as the knee bends and straightens. This type of prosthetic knee enables users to walk at different speeds and is the best choice for most people. It may be equipped with a microprocessor.

2.4.15 Knee prosthesis with microprocessor feature

Knee prosthesis with microprocessor feature have sensors that detect movement. The prosthetic knee provides good control when the foot is on the ground and when the leg swings forward. It can be programmed to compensate for stumbling and to enable users to descend stairs and ramps. Less energy is needed to use the prosthesis. The user achieves a more natural gait than would otherwise be possible.[28]

2.5 Prosthetic upper limb types

Options for hand prosthesis include:

- Precision (pincher) grip
- Tripod (palmar) grip
- Lateral (key pinch)
- Hook
- Spherical
- Sport-specific
- Myoelectric

2.5.1 Hand prosthesis with precision (pincher) or tripod (palmar) grip

A hand prosthesis with a precision grip has a thumb that opposes (presses against) the pad of the index finger. A hand prosthesis with a tripod grip has a thumb that opposes the pads of the index and middle fingers. Having a prosthesis with either a precision or a tripod grip enables the person to pick up or pinch a small object.

2.5.2 Lateral hand prosthesis

A lateral hand prosthesis enables the person to manipulate a small object (for example, turning a key in a lock) because it has a thumb that opposes the side of the index finger.

[28] http://www.merckmanuals.com/home/special-subjects/limb-prosthetics/options-for-limb-prosthesis

2.5.3 Hook prosthesis

A hook prosthesis enables the person to carry objects with a handle. It allows for thumb and finger flexion. A myoelectric hook improves the line of sight for functional grasp.

2.5.4 Spherical hand prosthesis

A spherical prosthesis allows thumb and fingertip flexion. A person using this type of prosthesis can grasp a round object (such as a door knob or electric bulb).

2.5.5 Sport-specific hand prosthesis

Sport-specific prosthesis can include a hand with a gripping device (for example, for golf, archery, or weight-lifting) or a hand with a mesh pocket for catching a baseball.

2.5.6 Myoelectric functional hand prosthesis

New developments in small, wireless electronic devices that control movement and sensation in a person's prosthetic hand allow for a more natural grip.

2.5.7 Elbow Prosthesis

Options for elbow prosthesis include:

- Body-operated
- Friction-operated
- Myoelectric

2.5.8 Body-operated elbow prosthesis

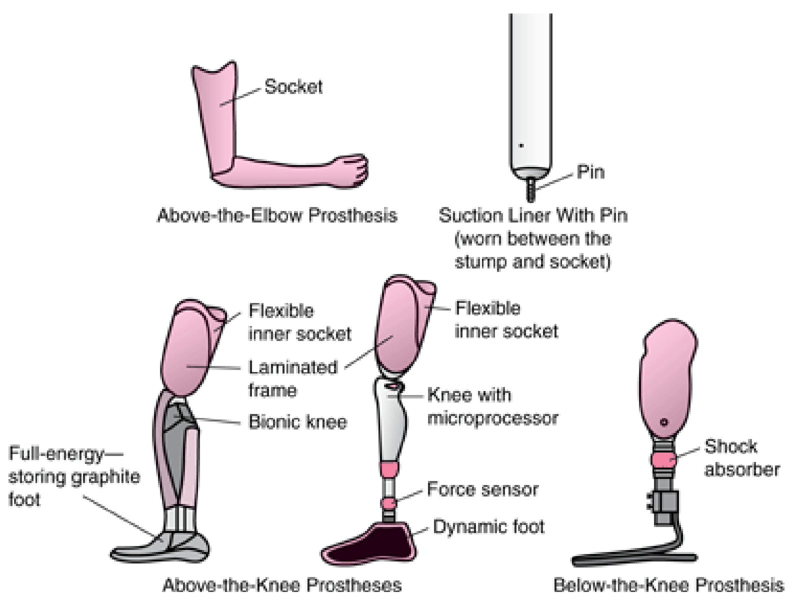
A body-operated prosthesis consists of a cable and harness that uses shoulder and back movement to move the arm. Although body-operated elbow prosthesis are lightweight, they are less attractive than other options and are sometimes bothersome to the user.

2.5.9 Friction-operated elbow prosthesis

A friction-operated prosthesis is raised or lowered by using the hand of the other arm. It is lightweight.

2.5.10 Myoelectric elbow prosthesis

Myoelectric prosthesis require no cables and provide more function. However, they can be heavy.



Types of Prosthesis[29]

[29] The Scientist, . "Prosthetic Legs." Scipolicy. Scipolicy.net, 19 May. Web. 15 Nov 2011. <http://www.scipolicy.net/prosthetic-legs/>.

2.6 Bionic limbs

The word bionic was coined by Jack E. Steele in 1958, possibly originating from the technical term bion (pronounced BEE-on; from Ancient Greek: βίος), meaning 'unit of life' and the suffix -ic, meaning 'like' or 'in the manner of', hence 'like life'. Some dictionaries, however, explain the word as being formed as a portmanteau from biology and electronics.

In medicine, bionics means the replacement or enhancement of organs or other body parts by mechanical versions. Bionic implants differ from mere prostheses by mimicking the original function very closely, or even surpassing it.[30]

A huge impact on Bionic limps is made from the field brain-computer interface (BCI), a main part of Artificial Intelligence. BCI plays a key role for robots and machines to be used in the general public who have no knowledge of software and hardware, in particular bringing benefit to the elderly and disabled.

2.6.1 Brain-Controlled Prosthetics research paper by Susan Perry

A very interesting paper on this area is " Brain-Controlled Prosthetics" written by Susan Perry. As she mentions in her paper, neuroscientists have help on the evolution of BCI technology and reach to a point where the user is able to control his bionic limb by only his brain. After decades of basic research into how the brain turns thought into physical action, nowadays there are bionic limbs that are using a tiny brain implant known as a brain-computer interface (BCI), in order to succeed the communication between the brain and the device. Also, at her paper she mentions that "*recent studies involving monkeys have shown that the brain can even accept a mechanical arm as its own, manipulating it like a normal limb to perform a complex motor task, such as grabbing and eating food*". This is very promising for the future, for further researches and more devices customizing better the needs of the user. Is leading to new methods of restoring movement to people with amputations.

More in detail, the research paper is referring to the State of the Art of the BCI. The goal is to send messages to the brain about movements. Scientists are using sensors that can detect and decode (with the aid of computer-programmed mathematical algorithms) the patterns of brain cell activity behind specific intended movements. Following, the reader will get into the two basic sensors used for this procedure, as it is analyzed on the paper by Susan Perry.

The one sensor "*records the activity of many brain cells together, either through the scalp (a technology called electroencephalography, or EEG) or just under the scalp (electrocorticography, or ECOG). The other does the same with dozens or more hair-thin microelectrodes in an array about the size of an aspirin implanted directly into the brain’s motor cortex, the area associated with movement. Each*

[30] https://en.wikipedia.org/wiki/Bionics

microelectrode in the array detects the electrical impulses, called spikes, of single neurons as well as the more diffuse signals seen in the EEG or ECOG."[31]

The conclusions of this research are many. Because the sensors cover a large area of the brain, the non-invasive EEG and the ECOG methods produce a not so accurate measurement of movement signals. The microelectrode array provides direct access to the signals related to movement, but must be inserted into brain tissue. Both types of sensors need to be recalibrate every day, as also their supporting equipment is quite big and non-portable.

Susan Perry concludes also in that there are already researches begun by recording the brain activity in the part of the cortex that processes proprioception, with the aim of creating computer algorithms that could be used to simulate the sensation in an artificial limb. Nevertheless, she mentions that scientists are very optimistic about the area of BCI and bionic limbs.

2.6.2 Bionic Arms

New research from Johns Hopkins University and DARPA shows how far sensing bionic limbs have come, proving that the technology is well on its way to offering real limb replacement. The breakthrough comes by way of patient interaction as much as advanced engineering, as work with real amputees shows how natural bionics sensing can really be.[32]

Fidelity in collecting control information from the brain or elsewhere in the nervous system is important — without that you can't control the arm itself — but a limb can only be so accurate so far without feedback information about the results of the movements it makes.

Classically, this refers to the fragile cup scenario, in which a person with a bionic hand must grasp a cup of water firmly enough that it doesn't fall, but gently enough that it doesn't break. The only way to do this is to sense how much pressure is being applied. And, crucially, the only way to interpret how much pressure is too much is to relay this information to the brain of a human who can judge the strength of things.

Currently available information is slightly vague about where the brain is being stimulated to produce these touch sensations. But since the volunteers were able to correctly identify the finger being touched with near-100% accuracy in the very first trial, it's likely that the electrodes are stimulating the sections of motor cortex already associated with finger sensation. This sets the technology apart from current sensing technology, which forces the patient to form new associations between totally new neural activity and familiar sensations. Other teams using a similar approach have achieved stunning preliminary results.

[31] http://www.brainfacts.org/About-Neuroscience/Technologies/Articles/2009/Brain-Controlled-Prosthetics
[32] http://www.extremetech.com/extreme/214244-sensing-bionic-limbs-are-here-and-they-work

Of course, having passing this sort of conceptual threshold, it won't be long before researchers start to improve the numbers involved — number that apply to natural human perception as well. Sensation coming from a bionic source does not have to be speed-limited by the diffusion of ions in solution, as are sensory neurons, or temperature-limited by the safety constraints of flesh. Bionic sensation could plausibly let a person put their hand down on a frying pan to test its temperature — and to judge it with their brain, the same as they would any reasonable level of heat.

They are developing the hardware necessary to restore the relationship between the brain and the outside world — and in the process developing the hardware necessary to completely change that relationship forever.

DARPA is funding this research because of the incredible potential it has to improve the lives of thousands of wounded veterans — but there's also plenty of emergent military and industrial value to be had, in any project of this type.[33]

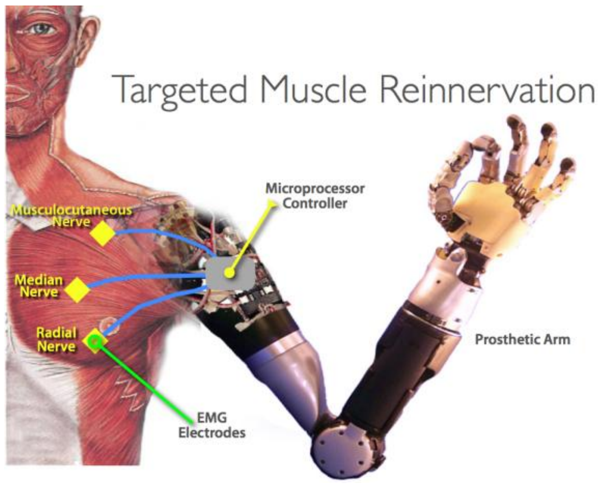
2.6.3 DEKA researches

The new generation of prosthetic arms has a different set of software -challenges and solutions. DEKA, the research firm founded by inventor (and 2009 PM Breakthrough Award winner) Dean Kamen, is developing the third generation of its bionic limb, known internally as Gen 3. It's backed by -DARPA's Revolutionizing Prosthetics program—a $100 million effort to create devices that are roughly equivalent in function to biological arms. Now awaiting FDA approval, Gen 3 has 10 degrees of freedom (typical motorized arms have only two or three) and a range of algorithms that mimic the precise control of its flesh-and-blood counterpart. By moving his or her foot, which operates a wireless controller, the user can engage various preset grasping patterns. Previous upper-limb models have used foot switches but with nowhere near the number of grip -options, nor the machine intelligence and the force sensors that guide the -artificial fingers and determine how much power should drive them. "The -results have been incredible," says Stewart Coulter, the Gen 3 project manager. "The other day, one of our testers was eating with chopsticks, -doing a better job than I could."

The second arm funded by the Revolutionizing Prosthetics program, the Modular Prosthetic Limb (MPL), developed at Johns Hopkins University, may lead to what many believe is the endgame for bionics: direct neural control. By embedding electrodes into a subject's existing nerves, or going through the skull and implanting them directly onto his or her cortex, researchers have been able to turn thoughts into action. In a study conducted in 2010 at the University of Pittsburgh, a quadriplegic pressed the MPL's hand against his girlfriend's. Through trial and -error, processors are taught to decrypt a user's thoughts and recognize a growing list of intentions. "The system's smart. It has to be," says Michael McLoughlin, Revolutionary Prosthetics' project manager at Johns Hopkins. "The algorithms interpret what the patient is trying to do, then do it."

[33] http://www.extremetech.com/extreme/214244-sensing-bionic-limbs-are-here-and-they-work

The MPL, in other words, isn't truly mind-controlled. The electrodes deliver orders, but it's the arm that decides how to carry them out. Or, rather, it's the network of machines-—each jointed segment and finger with its own processor—that makes up the arm. The state of the art in powered prostheses is in some ways stranger than science -fiction: a swarm of bots that obey the human mind, either through -cables that snake out of the skull or by taking their best collective guess at those thoughts. Stranger still, this is just the beginning.



Targeted muscle reinnervation[ii] allow natural control through the same neurons that controlled the lost limb.

2.6.4 Bionic Legs

Össur began selling the Symbionic model as the world's first -commercially available bionic leg on fall of 2011. It represents a significant shift in prostheses. The traditional half-measures, the stand-ins for lost limbs and senses, are being imbued with machine intelligence. Symbionic leg is, in fact, a robot, with sensors that detect its environment and gauge his intentions, and processors that determine the angle of his carbon-fiber foot as it swings forward. The same approach is being applied to prosthetic arms, in which complex algorithms determine how hard to grasp a water bottle or when to absorb the impact of a fall. Vision- and hearing-based prostheses bypass faulty organs and receptors entirely, processing and translating raw sensor data into signals that the brain can interpret. All of these bionic systems actively adapt to their users, restoring the body by serving it.

A mechanical knee typically goes rigid as the heel lands, supporting the user's weight, then unlocks when pressure is applied to the toe. If that toe contact comes too early the leg collapses under its owner. The Symbionic Leg isn't so easily fooled. Force sensors and accelerometers keep track of the leg's position relative to the environment and the user. Onboard processors analyze this input at a rate of 1000 times per second, deciding how best to respond—when to release tension and when to maintain it.

Since the leg knows where it is throughout each stride, achieving a rudimentary form of proprio-ception, it takes more than a stubbed toe to trigger a loose knee. If the prosthesis still somehow misreads the situation, the initial lurch of the user falling should activate its stumble--recovery mode. Like antilock brakes for the leg, the actuators will slow to a halt, and magnetically controlled fluid in the knee will become more viscous, creating resistance, as the entire system strains to keep the person from crumpling or toppling.[34]

Symbionic Leg 3 by Össur

2.6.5 Bionic Limbs and AI

Most prosthetic devices create their own health problems. Purely mechanical legs use a complex system of gears and analog triggers to allow people to walk, but users must hike up one hip with each step to keep the artificial toe from scraping the ground. Powered prosthetic arms tend to be locked in place during walking—and that dead weight throws off the user's balance and posture. Roughly 70 percent of amputees develop back and joint problems, and experts suggest that such "co--morbidities" force those who might be obese or in chronic pain to become even less mobile and less healthy, ultimately shortening their lives.

The answer, for now, is in the algorithms. Össur's Symbionic Leg eliminates hip hiking through a simple robotic twitch: The toe actuates upward during each step, performing what's called dorsiflexion. Other -algorithms are more sophisticated, interpreting a torrent of sensor data as specific types of terrain. If the foot lands at a higher elevation, with the knee bent, the leg assumes the presence of stairs

[34] http://www.popularmechanics.com/science/health/a7764/smart-bionic-limbs-are-reengineering-the-human-9160299/

and adjusts accordingly. If the toe tips up on contact and the heel dips down, the artificial intelligence (AI) suspects a slope and shifts the angle and resistance to assist in climbing.

We will further analyze the state of the art of prosthetic limbs constructed by Össur, Otto Bock as well Bebionic robotic arm by RSL Steeper, at chapter four.

2.7 Cost and source freedom

2.7.1 High-cost

A typical prosthetic limb costs anywhere between $15,000 and $90,000, depending on the type of limb desired by the patient. With medical insurance, a patient will typically pay 10%–50% of the total cost of a prosthetic limb, while the insurance company will cover the rest of the cost. The percent that the patient pays varies on the type of insurance plan, as well as the limb requested by the patient.[35]

Transradial (below the elbow amputation) and transtibial prosthesis (below the knee amputation) typically cost between US $6,000 and $8,000, while transfemoral (above the knee amputation) and transhumeral prosthetics (above the elbow amputation) cost approximately twice as much with a range of $10,000 to $15,000 and can sometimes reach costs of $35,000. The cost of an artificial limb often recurs, while a limb typically needs to be replaced every 3–4 years due to wear and tear of everyday use. In addition, if the socket has fit issues, the socket must be replaced within several months from the onset of pain. If height is an issue, components such as pylons can be changed.[36]

Not only does the patient need to pay for their multiple prosthetic limbs, but they also need to pay for physical and occupational therapy that come along with adapting to living with an artificial limb. Unlike the reoccurring cost of the prosthetic limbs, the patient will typically only pay the $2000 to $5000 for therapy during the first year or two of living as an amputee. Once the patient is strong and comfortable with their new limb, they will not be required to go to therapy anymore. Throughout one's life, it is projected that a typical amputee will go through $1.4 million worth of treatment, including surgeries, prosthetics, as well as therapies.

2.7.2 Low-cost

Low-cost above-knee prosthesis often provide only basic structural support with limited function. This function is often achieved with crude, non-articulating, unstable, or manually locking knee joints. A limited number of organizations, such as the International Committee of the Red Cross (ICRC),

[35] "Cost of a Prosthetic Limb". *Cost Helper Health*. Retrieved 13 April 2015

[36] "Cost of Prosthetics Stirs Debate", Boston Globe, 5 July 2005. Retrieved 11 February 2007.

create devices for developing countries. Their device which is manufactured by CR Equipments is a single-axis, manually operated locking polymer prosthetic knee joint.[37]

A plan for a low-cost artificial leg, designed by Sébastien Dubois, was featured at the 2007 International Design Exhibition and award show in Copenhagen, Denmark, where it won the Index: Award. It would be able to create an energy-return prosthetic leg for US $8.00, composed primarily of fiberglass.[38]

Prior to the 1980s, foot prosthesis merely restored basic walking capabilities. These early devices can be characterized by a simple artificial attachment connecting one's residual limb to the ground.

The introduction of the Seattle Foot (Seattle Limb Systems) in 1981 revolutionized the field, bringing the concept of an Energy Storing Prosthetic Foot (ESPF) to the fore. Other companies soon followed suit, and before long, there were multiple models of energy storing prosthesis on the market. Each model utilized some variation of a compressible heel. The heel is compressed during initial ground contact, storing energy which is then returned during the latter phase of ground contact to help propel the body forward.

Since then, the foot prosthetics industry has been dominated by steady, small improvements in performance, comfort, and marketability.

With 3D printers, it is possible to manufacture a single product without having to have metal molds, so the costs can be drastically reduced.[39]

A more detailed analysis about 3D Printing and Prosthetics will be on chapter five.

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37 "ICRC: Trans-Femoral Prosthesis – Manufacturing Guidelines" (PDF). Retrieved2010-10-03.
38 INDEX:2007 INDEX: AWARD Archived March 29, 2012 at the Wayback Machine
39 Robot arm startup taps 3-D printers in quest to make prosthetics affordable

2.8 Low-cost prosthetics for children

In the USA an estimate was found of 32,500 children (<21 years) that suffer from major paediatric amputation, with 5,525 new cases each year, of which 3,315 congenital.[40] Carr et al. (1998) investigated amputations caused by landmines for Afghanistan, Bosnia and Herzegovina, Cambodia and Mozambique among children (<14 years), showing estimates of respectively 4.7, 0.19, 1.11 and 0.67 per 1000 children.[41] Mohan (1986) indicated in India a total of 424,000 amputees (23,500 annually), of which 10.3% had an onset of disability below the age of 14, amounting to a total of about 43,700 limb deficient children in India alone.[42]

Few low-cost solutions have been created especially for children. Underneath some of them can be found.

2.8.1 Pole and crutch

This hand-held pole with leather support band or platform for the limb is one of the simplest and cheapest solutions found. It serves well as a short-term solution, but is prone to rapid contracture formation if the limb is not stretched daily through a series of range-of motion (RoM) sets.[43]

2.8.2 Bamboo, PVC or plaster limbs

This also fairly simple solution comprises a plaster socket with a bamboo or PVC pipe at the bottom, optionally attached to a prosthetic foot. This solution prevents contractures because the knee is moved through its full RoM. The David Werner Collection, an online database for the assistance of disabled village children, displays manuals of production of these solutions.[44]

2.8.3 Adjustable bicycle limb

This solution is built using a bicycle seat post upside down as foot, generating flexibility and (length) adjustability. It is a very cheap solution, using locally available materials.[45]

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[40] Krebs, D.E. and Edelstein, J.E. and Thornby, M.A. (1991) Prosthetic Management of Children with Limb Deficiencies.
[41] Carr, D.B. (1998) Pain and Rehabilitation from Landmine Injury
[42] Mohan, D. (1986) A Report on Amputees in India.
[43] Strait, E. Prosthetics in Deceloping Countries
[44] David Werner Collection:http://www.dinf.ne.jp/doc/english/global/david/dwe002/dwe00201.html
[45] Cheng, V. (2004) A victim assistance solution. http://www.ispo.ca/files/bicycle-prosthesis.pdf

2.8.4 Sathi Limb

It is an endoskeletal modular lower limb from India, which uses thermoplastic parts. Its main advantages are the small weight and adaptability.

2.8.5 Monolimb

Monolimbs are non-modular prosthesis and thus require more experienced prosthetist for correct fitting, because alignment can barely be changed after production. However, their durability on average is better than low-cost modular solutions.

Low-cost above-knee prosthetic limbs: ICRC Knee (left) and LC Knee (right)

3. Hugh Herr - "Leader of the Bionic Age"

Hugh Herr, who heads the Biomechatronics research group at the MIT Media Lab, is creating bionic limbs that emulate the function of natural limbs. In 2011, TIME magazine coined Herr the "Leader of the Bionic Age" because of his revolutionary work in the emerging field of biomechatronics– technology, marries human physiology with electromechanics. A double amputee himself, he is responsible for breakthrough advances in bionic limbs that provide greater mobility and new hope to those with physical disabilities.

3.1 Introduction on BiOM

Herr's research group has developed gait-adaptive knee prostheses for transfemoral amputees and variable impedance ankle-foot exoskeletons for patients suffering from drop foot, a gait pathology caused by stroke, cerebral palsy, and multiple sclerosis. He has also designed his own bionic legs, the world's first bionic foot and calf system called the BiOM.[46]

Herr is building sophisticated devices that aid human movement by mimicking nature. His lab is working to understand the tricks the human body uses for moving efficiently, and then translating that knowledge into robotic devices that can not only restore function to those who have lost it but enhance normal human capabilities. His lab's work to model the human ankle joint ultimately led to the development of the prosthesis Herr uses today, sold as the BiOM T2 by his startup company BiOM (formerly called iWalk). It is the first foot and ankle prosthesis that behaves, as he puts it, more like a motorcycle than a bicycle, meaning that it puts energy into the system rather than relying solely on human power.

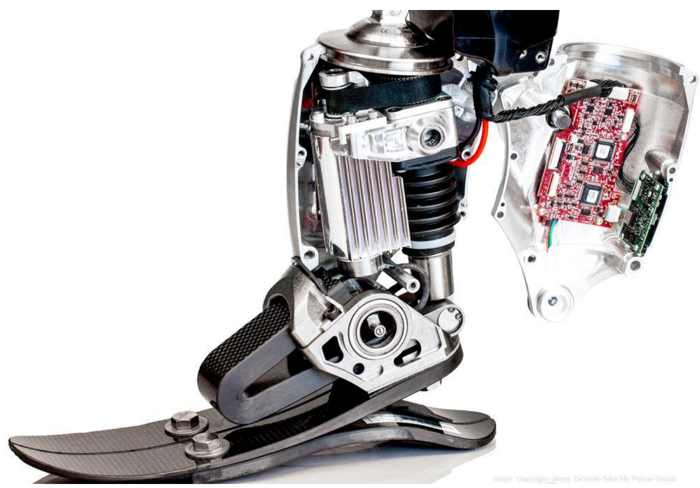
These walking and running devices designed in Herr's lab are the precursors to a system developed by his spin-off company BiOM

[46] https://www.media.mit.edu/people/hherr

In human walking, the calf muscle and the ankle joint contribute the most power. The BiOM T2 uses a battery to power a system of microprocessors, sensors, springs, and actuators; the joint provides stiffness during a heel strike to absorb shock, then power to help propel the lower leg up and forward during a step. The goal of such devices is to make prostheses more natural and, by lowering the energy costs of walking, reduce joint stress and fatigue. But bringing bionic devices into the clinic is not easy.

3.2 State of the Art

Herr has already tackled the problem of giving humans better, more seamless control over artificial limbs; his BiOM ankle prostheses adjust their torque and power in response to muscle contraction. Now he is going a step further, collaborating with surgeons and other researchers on ways to allow bionic limbs to be controlled directly by the nervous system, which he hopes to demonstrate in a human in the next few years. Whereas brain-machine interfaces would require invasive surgery for brain implants, he wants to connect electronic devices to the peripheral nerves at the site of the injury, allowing people to control bionic limbs with their existing nerves and potentially even perceive sensations in the limb.[47]



BiOM's ankle-foot bionic prosthetic device, which was developed by MIT Media Lab's Hugh Herr

[47] D. Morgenroth, A. Segal, K. Zelik, J. Czerniecki, G. Klute, P. Adamczyk, M. Orendurff, M. Hahn, S. Collins, A. Kuo. "The effect of prosthetic foot push-off on mechanical loading associated with knee osteoarthritis in lower extremity amputees," Gait & Posture, 34(4), 502–507, 2011.

3.2.1 Technology used

By late 2009, testing was underway on the PowerFoot BiOM, the first lower-leg system to use robotics to replace muscle and tendon function. Using onboard microprocessors and a three-cell ion lithium battery, the device actually propelled the user forward with each step, in the manner of organic muscle. For propulsion, the BiOM relied on a custom-built carbon-fiber spring—each time the user stepped down on the device, the spring was loaded with potential energy. On the up-step, that energy was supplemented with a small battery-powered motor.

Herr and his team knew that all steps are not created equal: Scrambling up a steep slope requires a very different gait—and very different parts of the body—from walking across a tennis court. So they developed a proprietary algorithm that measured the angle and speed of the initial heel strike of the BiOM, and controlled, via the microprocessors, the speed and angle of descent on the next step.[48]

According to Herr's research and tests, the device indicated that returned about 200 percent of the body's downward energy. A top-flight carbon-fiber prosthetic returned only 90 percent.

3.2.2 The BiOM Advantages

BiOM only has one product, which costs $40,000: an ankle-foot device that emulates muscle function, uses bionic propulsion and allows a user to walk with a normal gait. The BiOM Ankle is the only prosthesis with powered propulsion for enhanced mobility. [49] [50]

Power

- Emulates the function of your lost muscles and tendons.
- Energizes every step, so you will have more stamina to walk farther and faster – even up ramps, hills and stairs.

Control

- Mimics normal ankle movement to enable a more natural stride.
- Centers your alignment to reduce joint forces which may result in less pain.

[48] http://www.smithsonianmag.com/innovation/future-robotic-legs-180953040/?no-ist
[49] D. Hill, H. Herr. "Effects of a powered ankle-foot prosthesis on kinetic loading of the contralateral limb: A case series," IEEE International Conference on Rehabilitation Robotics, Seattle WA, June 2013
[50] A. Linberg, J. Shim, E. Wolf. "Use of a Powered Ankle Prosthesis to Decrease Work and Loading of the Intact Limb in Individuals with Transfemoral Limb Loss," American Orthotic & Prosthetic Association National Assembly, Boston MA, 2012.

Stability

- Dynamic resistance controls the ankle movement from heel strike until you push off your toe.
- Provides the balance you need to feel confident on any surface.

Clinical studies have shown that the BiOM Ankle can help people to:

- Walk at a faster speed
- Use less energy to walk
- Walk in a more natural manner
- Reduce stress on their joints
- Navigate varying terrain with less effort and greater speed

3.2.3 BiOM User Profile

Amputation Level

- One side amputated above knee or below knee
- Both sides amputated above and below knee
- Both sides amputated with one side above knee and the other below knee

Functional Level	K3, K4 (low to moderate impact; Ability to walk at variable speeds)
Maximun Weight	287 lbs (130 kg)
Foot Size	25-30 cm
Minimum Clearance	21.7 cm

Table about User's Profile

3.2.4 Bionic Benefits

Bionics is the science of constructing artificial systems that have some of the characteristics of living systems. The BiOM Ankle is the only prosthesis with powered propulsion that emulates lost muscles and mimics normal ankle movement for a natural stride. BiOM's benefits have been shown in clinical studies and published in peer-reviewed scientific journals. [51] [52] [53] Below is a summary of these major scientific findings:

[51] A. Grabowski, S. D'Andrea, H. Herr. "Bionic leg prosthesis emulates biological ankle joint during walking," Annual Meeting of the American Society of Biomechanics, Long Beach CA, 2011.

Increased walking distance and speed

With each step, the BiOM Ankle delivers powered propulsion to lift and drive you forward, smoothly transitioning your weight to the other foot. The BiOM Ankle conserves metabolic energy to reduce fatigue. In clinical studies, patients on the BiOM Ankle increased their walking speed an average 23%.

Improved safety and stability on variable terrain

The natural ankle slows down the body at heel-strike to control speed, before pushing off again. The BiOM Ankle uses dynamic resistance to replicate this deceleration which improves control and stability on any terrain. At the same time, the BiOM Ankle automatically adjusts the downward foot flex to match the angle of the ground.

Reduced joint forces and potential of osteoarthritis

People with lower limb amputations suffer a higher incidence of osteoarthritis due to an unnatural stride caused by conventional prostheses. A prosthesis that seems effective at first may soon cause joint pain that leads to osteoarthritis. The BiOM Ankle mimics normal ankle movement and provides powered push off which can normalize an unnatural stride, considered to be the root cause of osteoarthritis. Wearing the BiOM Ankle daily may help to delay osteoarthritis.

Easier climbing of ramps, hills and stairs

Ramps, hills and stairs can be a challenge for people with prostheses. You use your hips, residual limb and healthy side to provide power which can cause you to feel unstable and unsafe. Only the BiOM Ankle provides powered propulsion to drive you forward and upward, while balancing weight transfer. No other prosthesis attempts to do this. The BiOM Ankle replaces the power generated by your lost calf muscles.[54]

3.2.5 Drawbacks

There are still drawbacks to current bionic designs—ankle prostheses like Herr's go through one or two battery charges a day, for instance—so Herr and his colleagues are working to make prosthetic devices smaller, lighter, quieter, and more efficient. They're also involved in efforts to design more comfortable sockets to attach prosthetic limbs to the body. Humans "are soft and malleable," says Herr, "and we're not static; we change in time, we swell, we shrink. So how you attach the machine world to that is a really hard problem."

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[52]H. Herr, A. Grabowski. "Bionic ankle–foot prosthesis normalizes walking gait for persons with leg amputation," Proceeding of the Royal Society B, 279(1728), 2011.
[53] A. Grabowski, S. D'Andrea. "Effects of a powered ankle-foot prosthesis on kinetic loading of the unaffected leg during level-ground walking," Journal of Neuroengineering and Rehabilitation, 10(49), 2013.
[54] D. Morgenroth, G. A. Gellhorn, P. Suri. "Osteoarthritis in the Disabled Population: A Mechanical Perspective," The American Academy of Physical Medicine and Rehabilitation, 4(5S), S20-S27, 2012.

Technologists are still a long way from replicating the natural abilities of the body or building wearable devices that can dramatically boost its abilities.[55]

3.2.6 Future Work

Although BiOM currently has only one product on the market, another one of its devices — a powered orthotic device for people who have suffered a stroke and cannot move their toes — is in clinical trials at the U.S. Army's Center for the Intrepid in Texas. Herr's research accomplishments in science and technology have already made a significant impact on physically challenged people. The Transfemoral Quasipassive Knee Prosthesis has been commercialized by Össur Inc., and is now benefiting amputees throughout the world.

The company, which manufactures the prosthetics in Bedford, will also release a newer version early next year of its ankle-foot device that will be more durable and adjustable than previous versions. The device will also for the first time be available in two colors: black and aluminum.

[55] https://www.technologyreview.com/s/531411/grace-undersea/

4. Össur - Otto Bock

Artificial limbs have improved over thousands of years as better materials became available and our understanding of human physiology deepened. But nothing has advanced prosthetics as much as computing.

Based in Reykjavik, Iceland Össur is a global leader in prosthetics, braces, and orthopedic education. Össur, at the forefront of this revolution, has created the world's first microprocessor joint system that helps its users replicate and improve natural knee function. In the future, they'll be even smarter. The Rheo Knee, Power Knee, and Proprio Foot prosthetics all carry onboard artificial intelligences that help amputees use their bionic limbs with security and accuracy. Not only do the limbs move in a natural way and provide the strength to climb stairs foot over foot, they learn the user's gait.

Otto Bock is a German prosthetics company situated in Duderstadt. It was founded in 1919 by its namesake prosthetist, Otto Bock (1881–1960). It was created in response to the large number of injured veterans from World War I. The Otto Bock Corporation has been responsible for several innovations in prosthetics, including the pyramid adapter (a highly adjustable linkage for prosthetic parts) and the C-Leg, a computerized knee that adaptively varies its passive resistance to suit the patients' different walking gaits.[56]

In the subchapters following, I will analyze Rheo knee 3, Proprio foot, both made by Össur, as well as C leg 4 and Genium X3, two innovative prosthetic knees, constructed by Otto Bock. The reader will clearly understand the effect and the insert of Artificial Intelligence in the field of Prosthetics and the huge impact on users. Furthermore, I will mention on myoelectric-controlled arm prostheses and more specifically, Michelangelo Hand constructed by Otto Bock and Bebionic by RSL Steeper.

[56] https://en.wikipedia.org/wiki/Otto_Bock

4.1 Rheo knee3 - Proprio foot by Össur

Rheo knee 3

Proprio Foot

Össur's state-of-the-art bionic technology combines mechanics and electronics to effectively mimic the amputee's natural sensory and motor control functions. This advanced technology helps to reproduce accurately certain functions that have been lost due to amputation.[57] Both the Rheo knee 3 and Proprio foot (shown in images above) contain onboard computers that perform minute changes to the prosthetic to help it respond to variations in movement. The Proprio flexes to match terrain, and adjusts the ankle to fit different slopes. The Rheo knee 3 adjusts actuators to control leg swing. Together, this provides the user with increased security. The embedded Artificial Intelligence (AI) can learn an amputee's gait in just 15 steps, but continues to adjust as the user grows accustomed to the devices. These unique, intelligent and instinctive products utilize the very latest in artificial intelligence.

4.1.1 Rheo knee 3

Rheo knee 3 provides the most natural knee function among all microprocessor knees because it continuously adapts to the user and the environment while providing excellent stability and safety. The AI is also smart enough to match the powered movement with the user's natural gait. On level ground the knee uses its strength to help propel the user forward, letting him walk further without getting tired.[58]

[57] http://www.ossur.com/corporate/products/bionic-technology
[58] http://singularityhub.com/2009/08/27/bionic-limbs-with-artificial-intelligence/

Rheo knee 3 Characteristics

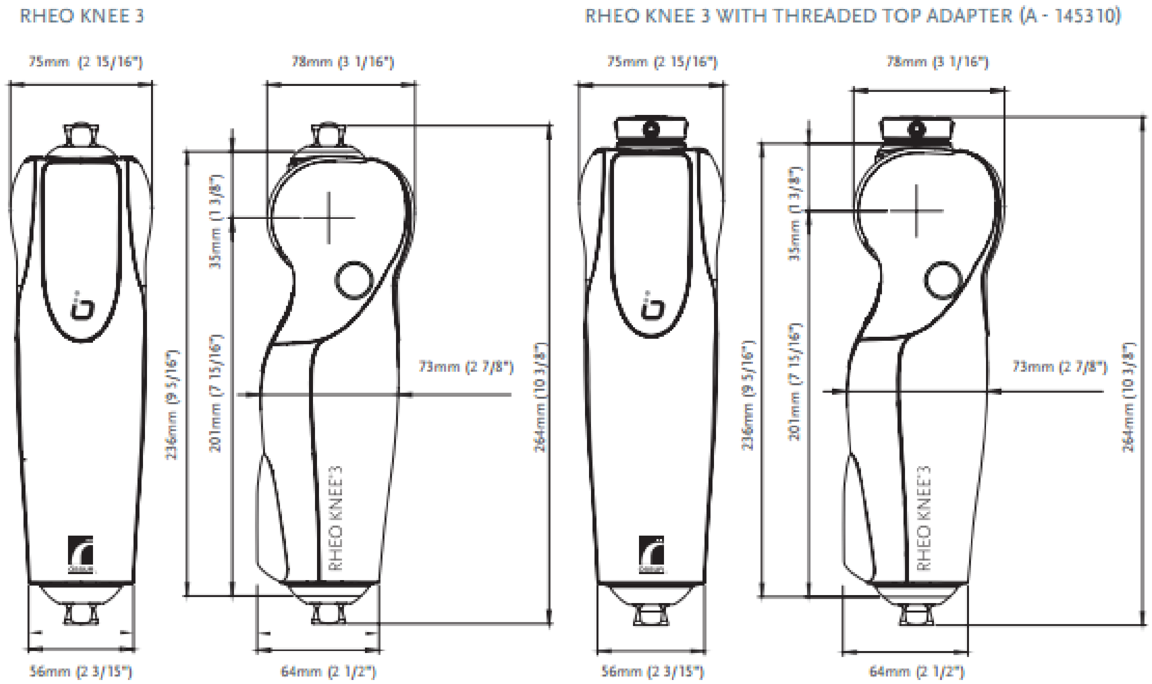
- Rheo knee 3 has an advanced actuator and resistance control that ensure the best possible resistance, e.g. more support in stair descent and minimum effort needed in level ground gait.
- The effortless swing initiation enables a smoother gait, even in crowds and confined spaces.
- There is a smart gait detection, including kinematic sensor technology, ensures stability and dynamic response in every situation.
- There is a magnetorheologic[iii] technology enables an instant response so that users never have to wait for the knee to catch up with them.
- Rheo knee 3 has an extension lock mechanism, in order to lock the knee in full extension and increase safety and comfort under specific circumstances.
- Also, ÖSSUR LOGIC app offers two levels of experience one for the user and another for the practitioner.[59]

User Information Amputation / *Knee Information*

Level: Transfemoral	Weight of Knee: 1.63kg (3.59lbs)
Impact Level: Low to Moderate	Build Height: 236mm (9 1/4")
Maximum Patient Weight: 136kg (300lbs)	Knee Flexion: 120º

Extras: Aluminum Frame Construction Redesigned, Extension Assist Mechanism[60]

[59] http://www.ossur.com/prosthetic-solutions/products/dynamic-solutions/rheo-knee-3
[60] http://assets.ossur.com/library/34749/RHEO-KNEE-3-Catalog-Page.pdf



Rheo Knee 3 Clearance

4.1.2 Proprio Foot

Proprio Foot is the world's first intelligent, motorized foot module. It provides unprecedented physiological benefits for transtibial[iv] amputees, including a wide, automated range of ankle flexion. Proprio Foot is known for featuring the latest biomechanical design and Artificial Intelligence technologies, creating a "smart" prosthetic that is capable of thinking for itself, responding to changing terrain, and transforming a user's approach to stairs and slopes, as well as level-ground walking.

"Össur's Proprio Foot has been designed to mimic natural sensory and motor control functions, and to more accurately reproduce biomechanical function that may have been lost due to amputation," said Mahesh Mansukhani, president of Össur Americas. According to Mansukhani, Proprio Foot 's design is intended to replicate the sensory experience and functionality of a natural foot and ankle, so users can experience a more symmetric and confident gait as well as enhanced safety. "Because Proprio Foot can learn its user's walking style, amputees no longer have to continuously focus on foot placement; the prosthetic automatically adjusts for them with every step," he said.[61]

The current state-of the art of Proprio Foot incorporates active dorsiflexion and plantar flexion[v]. Although incapable of significant power output, the active articulate provides improved toe clearance

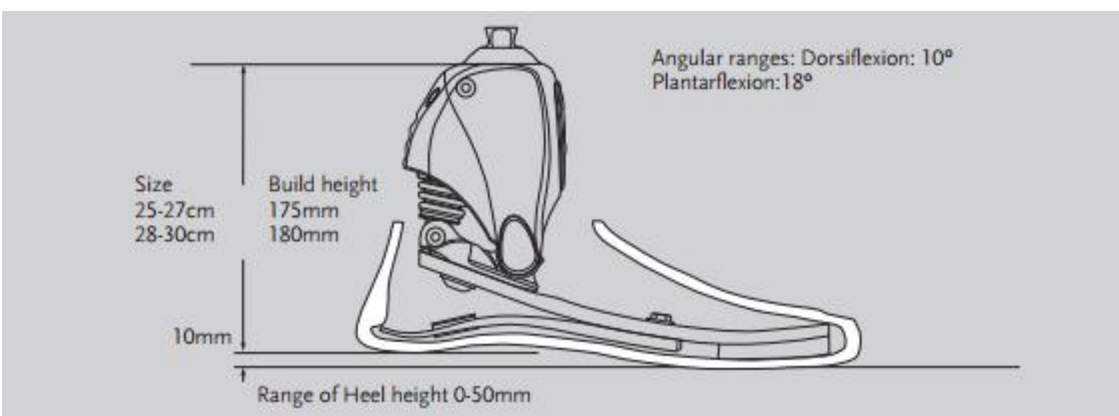
[61] https://www.ossur.com/about-ossur/news-from-ossur/239-ossur-s-newest-proprio-foot-bionic-prosthetic-to-be-highlighted-at-2011-aaop-meeting

during swing and adaptation to varied terrains. The device is controlled by special sensors implanted in the owner's leg muscle. When a signal from the brain reaches the sensors, they relay the signal to the Proprio Foot to make the appropriate action.[62]

Proprio Foot Characteristics

- Proprio Foot increases the ground clearance, reduces the risk of trips and falls and enhances safety and gait quality.
- It enables users to focus on their surroundings, instead of the walking terrain, offering a high degree of ground compliance, on all kinds of surfaces.
- Reduces strain on knees, hips and back.
- Enhances stability, efficiency and comfort on inclines, declines and stairs.
- Maintains symmetry and alignment while changing shoes.[63]

User Information	*Foot Information*
Maximum patient weight: 116kg	Categories 1-7 Sizes 25-30cm
Minimum patient weight: 45kg	Weight of proprio foot (Size 27, Cat 5) 1240g
Impact level: Low and moderate	Heel height adjustability up to 50mm
	Build height 18cm



Proprio Foot Clearance[64]

[62] http://laughingsquid.com/the-proprio-foot-a-brain-controlled-electric-prosthetic-foot/
[63] http://www.ossur.com/prosthetic-solutions/products/dynamic-solutions/proprio-foot
[64] http://assets.ossur.com/lisalib/getfile.aspx?itemid=6979

4.2 C-leg 4 - Genium X3 by Otto Bock

Following I will analyze the state of the art of C Leg 4 and Genium X3, two of the most innovative artificial knees constructed by Otto Bock.

C leg 4

Genium X3

4.2.1 C leg 4

Otto Bock introduced the world to the very first fully microprocessor-controlled knee in 1997. The C-Leg caused an immediate sensation and has since become the most popular microprocessor prosthetic leg in history — with clinical studies to back it up. Since its introduction, over 40,000 people have taken advantage of the C-Leg's proven function and stability and helped to make C-Leg technology the standard of care for above knee amputees. The C-Leg 4 continues the industry-leading tradition of improving outcomes for more than 60,000 fittings worldwide. With studies citing increased stability and reduced falls, the C-Leg 4 is weatherproof, can be controlled with the Android Cockpit app, and makes walking backward easier.[65]

One of the many improvements that make C-Leg 4 uniquely easier to use is a patented Inertial Motion Unit control feature that improves the transition to swing phase and makes walking backwards safely possible. By refining C-Leg 4 function, changing walking speeds are controlled efficiently and effectively, even when steps are small or surfaces are challenging.[66]

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[65] http://www.Otto Bockus.com/c-leg.html
[66] http://www.Otto Bockus.com/media/local-media/prosthetics/lower-limb/c-leg/files/cleg4brochure.pdf

Real-time swing phase control fueled by 3D motion analysis

Since motion occurs in three dimensions, the C-Leg 4 utilizes multiple data sources to ensure swing phase resistance is precisely what it needs to be at every moment of every step. As a result, C-Leg 4 lets the patient easily navigate ramps, stairs, and nearly every type of challenging surface. 3D motion analysis also supports patients when walking backwards. Because the knee knows where it is in space at all times and the minimum forefoot load has been eliminated, it will not flex as a patient steps backwards.

C Leg 4 Characteristics

Adapting automatically to every step

With C-Leg 4, the knee is ready for your patient's next move. Enhanced stumble recovery, improvements in stance and swing phase control, and the addition of Intuitive Stance offers more support for activities of daily life.

More clearance, more choice

A new, naturally-shaped frame design has reduced the system height, letting people with less clearance benefit from the stability and smooth function of the C-Leg 4. Otto Bock's recommended foot choices offer a range of clearance and function as well.

Wet or dry

Everyday life occasionally gets a little damp. The weatherproof C-Leg 4 can handle it, whether your patient runs into a rainstorm or gets splashed while watering the garden.

MyModes

C-Leg 4 helps people master everyday life more confidently. With two additional MyModes, the knee can be adjusted to meet an individual's specific requirements for unique activities such as biking, dancing, or golfing.

Smart control

For the first time, patients can quickly switch between MyModes and monitor battery life using the new Cockpit app for Android. The optional remote control also supports this functionality. Both options use integrated Bluetooth technology.

Be seated

The new sitting function automatically switches C-Leg 4 to free-swing when the individual sits down, resulting in a relaxed position and activation of a battery save mode.

4.2.2 Genium X3

The result of a collaboration between the US military and Ottobock, the Genium X3 is quite simply the world's most technologically advanced microprocessor prosthetic leg. The goal was to develop a more durable and intuitive prosthetic leg to help injured service members with above knee amputations return to normal activities of daily living as well as active duty if they choose. In addition, the innovative Walk2Run mode is ideal for running short distances and start-and-stop running such as across a street, down the hall or to catch a bus. In that mode, the X3 detects a walk-to-run transition and the swing angle automatically increases, with no preflexion.

The X3 is "ruggedized" based on conditions an active duty military member might face and is up to the challenge of adverse and rough terrain. The most natural gait possible with an accelerometer and a gyroscope that is able to intuitively tell where a user's leg is in space. These are the same technologies used in Wii™ gaming systems and smartphones and cameras and allows for a virtually natural gait. That means less worry of a stumble or fall and less concentration needed when on the move. Real-world mobility more physical capabilities for the real world than any other prosthetic leg including running, walking backwards, crossing obstacles in a more anatomically correct way, and climbing stairs step-over-step without massive compensating movements – -an action that previously appeared impossible for those with above knee limb loss.

Nevertheless, Genium X3 offers improved battery life and an automatic "sleep" mode. That translates into five plus days of use without the need for a recharge and results in greater independence. 5 activity modes, plus a "silencer" Programmed using a laptop and Bluetooth technology, five activity modes can be set for biking, golfing, driving, etc., and are activated using a key fob-sized remote. A mute mode is also available that silences all vibration and beep signals of the leg when needed for activities such as meetings, movies, hunting and more.[67]

Genium X3 Characteristics

Preflexvi

The Genium X3 maintains a hydraulically controlled 4˚ of preflexion of the knee joint when the user's heel starts his stride ("heel strike"), which allows his foot to reach full contact more quickly and gives him a more stable start to his step.

Adaptive Yielding Control

Intelligent knee flexion (max. 17˚, depending on the situation) gives the user more efficient, intuitive control of his prosthesis. Because the knee is flexed it better absorbs shocks and helps limit future orthopedic problems.

[67] http://www.prostheticsinmotion.com/technology.html

Dynamic Stability Control (DSC)

The heart of the system: DSC continuously samples multiple environmental inputs—including a gyroscope and 2-axis accelerometer—which determine the appropriate resistance (support) and release at any time during the user's walking cycle. That means optimum security for the user.

- Supports multi-directional movement, so the user can take quick steps— forwards, backwards, and sideways.
- Increases stability when walking backwards.

Adaptive Swing Phase Control

The user gets precise control of his lower leg no matter what his walking speed is. This also helps to prevent falls.

- The quality of his swing phase (when his leg is off the ground) is far superior to other prosthetic knee joints.
- It's easier to swing his knee through during a stride, helping reduce the risk of stumbles and falls.
- There are no limits on walking style: quick, slow, irregular.[68]

Patient weight	125kg / 275 lbs
Weight of knee	3.1 lbs
Weight of the tube adapter	10.5 oz
Adjustable activity modes	5
Operating with fully charged battery	Approx. 5 days
Knee flexion angle	Max. 135 degrees

4.2.2.1 The Genium Bionic Prosthetic Knee System

This state-of-the-art microprocessor-controlled knee joint utilizes a complex sensory system and sophisticated rule sets to mimic natural gait more closely than any other prosthetic knee. With multiple environmental inputs (including a gyroscope and an accelerometer), the Genium delivers unmatched functionality, including special features to help step over obstacles and ascend stairs.

The Genium builds on the knowledge gained from their experience with tens of thousands of C-Leg® wearers and decades of development. The unique Genium technology is not a next-generation C-Leg, but is a sophisticated new technology platform built to gather exponentially greater microprocessor inputs that result in very precise responses.

[68] http://www.ottobock.co.uk/prosthetics/lower_limb_prosthetics/prosthetic-product-systems/genium_x3-prosthetic-leg/

For the wearer, motion becomes intuitive. Barriers and obstacles become an unconscious part of life instead of an interruption. Whether making a fast turn-and-grab to catch up with a runaway toddler, changing speed dramatically or backing up to navigate a crowd, or simply stepping over an obstacle instead of going around, the Genium makes it all easier without risking stability.[69]

4.3 Myoelectric-controlled arm prostheses

Few parts of the human body are as important and complex as the hand. Only the perfect interplay of nerves, tendons, a total of 27 bones, 39 muscles and 36 joints allows people to handle their everyday tasks. upper-limb prosthetics actually accounts for a small fraction of the field of prosthetics. There are an average of 18,496 upper-extremity amputations every year, compared to 113,702 of the lower extremity. Of those, only 1900 are above the wrist.1 Among upper-limb amputees, typically fewer than half wear prosthetic arms. All told, lower-extremity patients outnumber upper-extremity patients 30:1. This small population means that most prosthetists do not get much experience in upper-limb patient care. [70]

Myoelectric-controlled arm prostheses are externally powered prostheses, which means that they are not driven by the muscle strength of the patient, but with the aid of electric power. The word “Myo” is derived from Greek: "μυς" mys (“muscle”). A biochemical process generates electrical tension in the microvolt range every time a muscle contracts. This tension can be measured on the skin. This also applies to the muscles remaining after an amputation. With myoelectric arm prostheses, muscle tensions from the residual limb are usually read by two electrodes – small children start with one. The low myoelectrical impulses that lie in the microvolt range are then amplified and forwarded to the electronics of the prosthesis in the form of control signals.

Two very interesting models of myoelectric-controlled arm prosthetics are Michelangelo Hand constructed by Otto Bock and Bebionic manufactured by RSL Steeper. Following I will analyze the State of the art of those two as an example of Upper limb Prostheses.

[69] http://www.prostheticsinmotion.com/technology.html
[70] http://www.upperlimbprosthetics.info

4.3.1 Michelangelo® Hand by Otto Bock

The Michelangelo Hand is the most technologically advanced and functional prosthetic hand available. And as the heart of the new Axon-Bus® prosthetic system, it offers unrivalled benefits and new freedom of movement for the user. The Michelangelo Hand has a thumb that can be separately positioned using muscle signals—offering more hand positions than any other prosthetic hand available. In order to achieve its incredibly natural movement patterns, the hand is equipped with two drive units. The main drive is responsible for gripping movements and force, while the thumb drive allows the thumb to be moved in an additional axis of movement—including an open palm and lateral pinch. The thumb, index and middle finger are actively driven, while the ring and little fingers passively—and naturally—follow the other fingers. The Michelangelo® Hand helps users more easily integrate everyday movements such as cooking, driving—even playing cards—into their everyday life.

Michelangelo® Hand

4.3.2 Bebionic by RSL Steeper

Designed in the United Kingdom, the Bebionic hand is manufactured by RSL Steeper and is available worldwide. The first version of the Bebionic hand was launched at the World Congress and Orthopädie & Reha-Technik, Trade Show, Leipzig, Germany in May 2010.

Unlike previous prosthetic hands, which may use a hook, the Bebionic hand uses individual motors and microprocessors. [71]The bionic hand works on electrical impulses generated from the biceps and the triceps of the amputee. These electrical impulses move the prosthetic hand into the correct position. The cutting-edge robotic hand has 337 mechanical parts, magnets for improved speed and strength, and bubble fingertips for precision in handling objects. The bionic hand was made with small parts, specifically in scale for women and teenagers, so it's not too big. Steeper says the Bebionic small hand copies the capabilities of a real hand with 14 different precision grips. There are sensors activated by muscles in the arm to make the hand move along with each finger having its own motor to move by itself.

Here are some more features of the Bebionic small hand, which retails for about $11,000:

- Powerful microprocessors constantly monitor the position of each finger for reliable control over hand movements
- Proportional speed control gives you precision control over delicate tasks
- Four wrist options (Quick Disconnect, Multi-Flex, Flexion and Short Wrist) that have their own functionality
- Strong enough to carry up to 99 pounds
- Bebalance software that can be managed, monitored and configured wirelessly

Bebionic

[71] https://en.wikipedia.org/wiki/Bebionic

4.4 Who can afford?

Physically disabled persons spend their life earnings and savings paying for prosthetic knees, feet and services needed to maintain the standard of prosthetic parts every year. A new leg from foot to top costs about $11,000 for the cheapest prosthetic solution. In many cases this only allows a disabled person to walk to limited extent. With such a solution a disabled person will never have the opportunity to swim or run, go hiking or similar.

For example, an above knee amputee. He will need 5 major parts:

1. the socket/shaft ($6000)

2. the knee (the best knee sold for $60,000)

3. the foot (best foot sold for ($7000)

4 .the liner ($900 ever 5-7 months, no liner, no walking)

5. a check socket ($ 2000 - $3000)

Gone are the days where legs were made and sold by orthopedics. Nowadays, the price of prosthetic legs is extremely costly. Most orthopedics are by law required to go by the prices of Otto Bock and Össur which close to double the prices of prosthetic leg parts. A prosthetic knee sold by Otto Bock or Össur through orthopedics can today cost up to $60.000. There is no opting out for orthopedics in this.

It is evident that these are price levels only a few can afford and ultimately this affects the quality of life of disabled persons. Taking a walk to the park with the child, making dinner or even going to the post box are all normal daily tasks that appear as overwhelming challenges for a physically disabled person. The price to walk are in some countries equivalent to the price of a house. Fortunately, many autonomous people, University students or small teams of new scientist, have take into account that not everyone can afford a hand or knee Kit by big companies. Therefore, there are many constructions, low cost, maybe not that evolutionary, but surely effective and useful for any disabled person, that cannot afford.

3D Printing and low cost materials' constructions have played a major role in this. 3D Printing and Prosthetic limbs will be analyzed in the next chapter.

An example of low cost knee prosthetic limb has been presented on TEDWomen on 2014 by Krista Donaldson. Donaldson is the CEO of D-Rev (short for Design Revolution), a non-profit product development company headquartered in San Francisco, California. D-Rev's products include the ReMotion Knee, a polycentric prosthetic knee for above-the-knee amputees.[72]

[72] http://d-rev.org

The ReMotion Knee, previously called the JaipurKnee, is a prosthetic knee joint for above-knee amputees. The JaipurKnee was developed by students at Stanford University in 2009. The student project worked with the Jaipur Foot Organization or Bhagwan Mahaveer Viklang Sahayata Samiti, Jaipur (BMVSS) to develop a low-cost knee joint to be used at BMVSS clinics in India and temporary fitting camps around the world. A group of Stanford University students started ReMotion, an independent company to pursue the design and distribution of the prosthetic knee joint. D-Rev acquired ReMotion and all of its IP in 2012. Amputees were first fit with the ReMotion Knee in May 2013. The ReMotion Knee weighs 0.88 lb/400g and is produced using injection molding, allowing for centralized manufacturing and a slimmer device profile. The ReMotion Knee has a projected retail price of $80 USD.[73]

Although it might not be competitive to the standards developed by Otto Bock and Össur it represents a world's difference for a disabled person. It gives him back the right in life, in walking, in enjoying sports etc.

[73] https://en.wikipedia.org/wiki/D-Rev

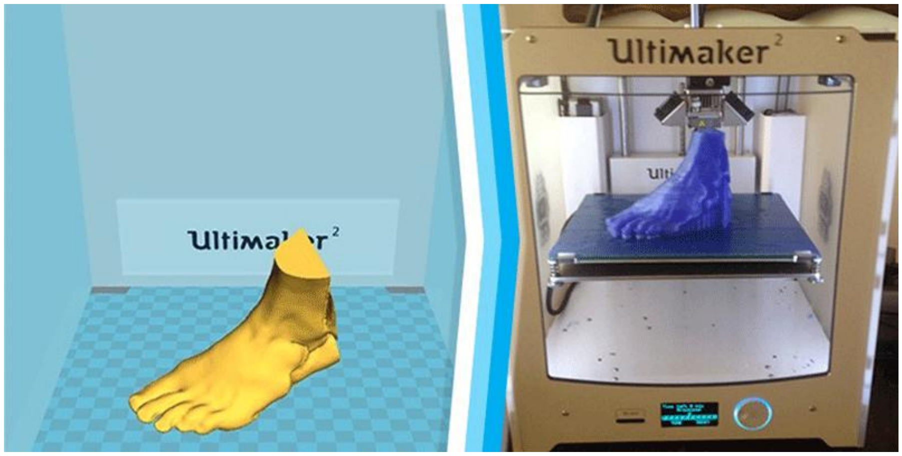
5. 3D Printing

As we will see the cost of a 3D printed prosthetic limb is much lower than a C-leg from Össur, or Michelangelo by Otto Bock, for example. We will see some paradigms of 3D printed prosthetics that are much more affordable to people, and more specifically to developing countries. Firstly, we will mention *Dextrus,* an example of *e-Nable* project, which uses low-cost 3-D printers to create high-power hands. Another example of 3D printed prosthetic hand is made by *3DLifePrints*. Furthermore, I will analyze *Exo* full leg, designed and constructed by William Root, which has a very interesting design and not only. It is possible to use low-cost 3D printing to make prosthetics at a fraction of the cost of traditional manufacturing methods.

5.1 Introduction

To understand the impact that 3D printing is having, it's important to start with a workable definition. 3D printing—also known as "additive manufacturing"—is the process of creating a three-dimensional object by applying, or adding, material in successive layers through the control of a computer. The 3D printing process, in basic terms, includes the following steps:

1. The manufacturer creates a digital model of the object to be produced, normally by using a computer-aided design (CAD) program and employing some form of 3D scanning.
2. The CAD model is converted into an appropriate file format, such as STL (stereolithography[vii]).
3. The STL file is transferred to the computer that directly controls the 3D printer (a process similar to transferring a file to a standard printer when printing a document).
4. The 3D printer is readied for the job. Containers are loaded with the appropriate printing materials (polymers and binders, for example), and a foundation tray for the finished object is set up.
5. The printer builds the object, layer by layer. This process can take hours, or even days, depending on the size and complexity of the object and the materials used to create it.
6. Once the 3D printer has completed the building process, the object is removed from the machine. The object may require some post-manufacturing actions, such as brushing and polishing, as well as the removal of water-soluble supports. The object may also require time to cure before it can be used.



3DLifePrints CAD design and 3D Printer[74]

5.1.1 3D Printing - Medicine and Health

Medicine and Health is probably the field where the most innovative applications of 3D printing technology are happening today. The idea of creating new, living body parts to replace ones that are damaged seems only possible in a sci-fi film, but such projects are underway at universities, hospitals and research centers around the world. These 3D printing projects include bioprint tissues and organs, customized implants and prostheses, anatomical models for surgical procedures, and growing embryonic stem cells.[75]

5.1.2 Biomedical Engineering and Technology

This discipline combines science and engineering with biology and physiology to analyze and address problems within health and health care delivery. Graduates of this degree can go on to careers focused on developing and improving medical devices and procedures, which can include responsibilities such as creating and evaluating artificial organs, prostheses, or new equipment to maximize human performance.

Bioprinter

Bioprinting can be thought of as a subfield of 3D modeling. The main difference is focus, with 3D bioprinting concerning the production of living human tissue. Individuals in the bioprinting field are responsible for creating models that are used as the basis to 3D print any number of living body parts and even replacement organs.

[74] http://3dprintingindustry.com/2015/03/24/mobility-takes-whole-different-meaning-3d-life-prints-africa-asia/
[75] http://www.computerscienceonline.org/cutting-edge/3d-printing/

Prosthesis and Implant Designer

3D printing of prostheses and implants is distinguished from bioprinting in that the devices created are artificial. Prosthesis and implant designers employ a variety of software programs in creating customized implants to suit specific patient needs.

Pharmaceutical Technologist

Pharmaceutical technologists employ 3D printing systems to produce highly individualized medications. 3D printing of medications allows for extremely precise dosages that can be accurately reproduced in quantity and in a wide range of formulations (pills, tablets, liquids, etc.).

5.1.3 Rehabilitation of crippled animals

Printed prosthetics have been used in rehabilitation of crippled animals also. In 2013, a 3D printed foot let a crippled duckling walk again.[76] In 2014 a chihuahua born without front legs was fitted with a harness and wheels created with a 3D printer.[77] 3D printed hermit crab shells let hermit crabs inhabit a new style home.[78] A prosthetic beak was another tool developed by the use of 3D printing to help aid a bald eagle named Beauty, whose beak was severely mutilated from a shot in the face. Since 2014, commercially available titanium knee implants made with 3D printer for dogs have been used to restore the animal mobility. Over 10,000 dogs in Europe and United States have been treated after only one year.[79]

[76] "3D-Printed Foot Lets Crippled Duck Walk Again"
[77] Pleasance, Chris (18 August 2014). "Puppy power: Chihuahua born without front legs is given turbo-charged makeover after being fitted with 3D printed body harness and a set of skateboard wheels". The Daily Mail. Retrieved 2014-08-21.
[78] Flaherty, Joseph (2013-07-30). "So Cute: Hermit Crabs Strut in Stylish 3-D Printed Shells". Wired.
[79] "3D Systems preps for global launch of 'printed' knee implants for dogs". *FierceAnimalHealth.com*. Retrieved 13 April 2015.

5.2 State of the Art

Following, we will analyze the State of the Art of Prosthetics made by 3D printers. 3D Printing industry has focused on higher-limbs prosthesis. Some steps have been made on the lower-limb amputations, but mostly on higher-limbs. Following I will analyze three 3D Printed artificial limbs that got my interest. Then on the subchapter 5.6 we will be able to compare the technology used on prosthetics by 3D printers and constructing companies like Otto Bock and Össur.

5.3 Dextrus by Open Hand Project

In October 24, 2014, a five-year-old girl born without fully formed fingers on her left hand became the first child in the UK to have a prosthetic hand made with 3D printing technology. Her hand was designed by US-based e-NABLE , an open source design organization which uses a network of volunteers to design and make prosthetics mainly for children. The prosthetic hand was based on a plaster cast made by her parents.[80] A boy named Alex was also born with a missing arm from just above the elbow. The team was able to use 3D printing to upload an e-NABLE Myoelectric arm that runs off of servos and batteries that are actuated by the electromyography muscle. With the use of 3D printers, e-NABLE has so far distributed more than 400 plastic hands to children.

The work of the Open Hand Project is being continued by Open Bionics. Open Hand Project is an open-source project which means that all of the know-how you need to create one of these magnificent devices will be available online. That way, anyone can improve and customize the designs themselves and then upload them for everyone to share.

Dextrus uses electric motors instead of muscles and steel cables instead of tendons. 3D printed plastic parts work like bones and a rubber coating acts as the skin. All of these parts are controlled by electronics to give it a natural movement that can handle all sorts of different objects. The hand can be connected to an existing prosthesis using a standard connector. It uses stick-on electrodes to read signals from their remaining muscles, which can control the hand, telling it to open or close.

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[80] BBC News (October 2014). "Inverness girl Hayley Fraser gets 3D-printed hand", BBC News, 01 October 2014. Retrieved 02 October 2014.

Dextrus

3D-printable prosthetics are changing the face of medicine, as engineers and physicians are able to develop prosthetics that are fully customized to the wearer. Consumer 3D printing is leading to an even bigger revolution: "DIY" assistive devices that can be printed by virtually anyone, anywhere.[81]

5.3.1Electronics

The Dextrus hand uses electronics to interpret signals and convert these into hand movements. These electronics will do the following:

1. Amplify the small Electomyographical signals from the user’s muscles and filter them to remove unwanted frequencies.
2. Provide power to the various components and house the microcontroller.
3. Amplify the signals from the microcontroller to power the motors.
4. Read current feedback from the motors to know when an object is grasped.

5.3.2 Mechanical Parts

The Dextrus hand contains many mechanical components including 3D printed plastic parts, tendons, nuts and bolts. Once the Dextrus design is complete, you’ll be able to find everything you need to build your own here on the website. Suppliers will be included where possible but it may be difficult to get international suppliers for all parts.

[81] http://3dprint.nih.gov/collections/prosthetics

5.3.4 Software Development

One of the biggest concerns in the 3D printing industry is the need for better and, perhaps most importantly, more user-friendly software to design and manufacture 3D printing products. As a result, the industry has become a top destination for software development professionals. Software developers in this field will write code to help improve 3D printing products as well as work cross-functionally with various teams, typically focusing on important aspects such as testability, maintainability, and scalability.[82]

Computer Programmer

3D printing relies on skills and knowledge in science, technology, engineering, and math (as well as art), making computer programming another solid option for students interested in the field, like students of our Master Degree. These professionals use their expertise to write programs that produce solid structures of all shapes and sizes.

CAD or BIM Architect

CAD and BIM architects use software programs to design, generate and manage computer/digital representations of physical structures and infrastructures.

Research and Development (R&D)

R&D professionals explore new materials and processes and come up with new and better ways to develop—or improve—3D devices.

[82] http://www.computerscienceonline.org/cutting-edge/3d-printing/

5.4 3DLifePrints

3DLifePrints, is a Kenya-based enterprise that specializes in delivering low-cost 3D printed prosthetics to amputees in developing and emerging nation. Basing its research and work upon an extensive network of contacts through several emerging nations between Africa and Asia, 3DLifePrints has focused on truly bringing prosthetic manufacturing capabilities to the places where people need them most, understanding the specific local necessities, both in terms of functionality and aesthetics. Developing a fully flexible prosthetic hand, while significantly more complex to produce, can offer many advantages in terms of making the prosthetic more similar to a real hand, in form and function. This particular prosthetic system, which also includes a harness to activate the mechanical grip, only cost $49 to produce and 3D technologies play a role in the 3D scanning of a patient's remaining limb, as well, in order to make the prosthesis fit properly.[83] The 3D Life Print team works to develop surfaces that resemble the human skin, by mixing colors. The technology is not quite there yet, but it is improving rapidly.

In September 2015, 3DLifePrints has released its first 3D printed fully flexible prosthetic arm. This limb 3D printed in nylon, while Recreus's flexible filament[84] was used for the hand. 3D printing was carried out on a DeltaWASP 2040[85] and a Witbox 3D printer[86]. A 3D scanner was also used to add more realistic details to the outer surface of the hand. Other components were created with locally sourced break cables (for the gripping mechanism), fishing wire (to connect all five fingers to one cable), velcro, and a nylon strap.

Summing up the $5 for the harness strap, $6 for the break cable, $32 for the filaments, $2 for the velcro, and $2 for the fishing wire, the total is only $49, but the results are comparable – or even superior – to much more expensive, traditionally manufactured prosthetic products. The fact that real innovation in this field is coming for Cambodia is yet another practical demonstration of the potential of distributed manufacturing. 3DLifePrints' 3D scanning and 3D printing skills grow enormously, to the point that their prosthetics – based on modified e-NABLE designs – are often superior to other ones that cost more than 50 times as much.

3DLifePrint first printed prosthetic arm

[83] http://3dprintingindustry.com/2015/09/11/cambodian-fisherman-receives-first-fully-flexible-prosthetic-arm/
[84] http://recreus.com/en/
[85] http://www.personalfab.it/en/products/deltawasp-20-40/
[86] http://www.printme3d.com/bq-witbox.html

5.5 Exo

William Root, a recent graduate from the Pratt Institute in New York City, has developed a system to 3-D print super-lightweight prosthetic legs with stealth styling. Root's prosthetic concept combines his interests in aesthetics and biomechatronics, as well as inquiries into the preferences of amputees. Root's improved process starts by making a scan of the patient's anatomy. He envisions using a technology fromMIT's Biomechatronics lab called FitSocket which uses an array of pressure sensors to gauge the softness or stiffness of a patient's remaining tissue. With this data, a nearly perfect "socket," the term for the interface between the patient's body and prosthetic, can be manufactured.

Using the same data, Root would extrapolate a 3-D model of patient's full leg which is turned into a triangulated mesh. "It has the maximum strength for the least amount of material with the added benefit of looking really slick," says Root. A stress analysis tool helps determine weak-points on the model and software increases the mesh density of the structure to compensate. Though Root notes further analysis of the weight distribution and point loads will be needed to create a fully functioning limb.

The result is a jet black prosthetic made from sintered titanium powder or high-strength plastic that makes the wearer look as if they're materializing from a video game. "Prosthetic limbs are stigmatized because they are so inhuman; most aftermarket companies that try to address this problem attempt to create a realistic-looking leg, which crosses into the uncanny valley," says Root.[87]

To Root, legs made from flesh-colored rubber are a symptom of a thought process where prosthetics are considered mass produced products rather than the ultimate form of wearable. "With prostheses you are essentially designing a person, their body already dictates the form," he says. "Each leg needs to be as unique as its owner." He envisions future iterations of Exo where colors or patterns of the mesh could be modified to suit the wearer's personal sense of style.

Exo by William Root

[87] http://www.wired.com/2015/01/3-d-printed-prosthetics-look-fit-sci-fi-warrior/#slide-1

5.6 Comparison of technology

5.6.1 Current technology and manufacturing

Over the years there have been advancements in 3D Printed artificial limbs. New plastics and other materials, such as carbon fiber, have allowed artificial limbs to be stronger and lighter, limiting the amount of extra energy necessary to operate the limb. This is especially important for transfemoral amputees. Additional materials have allowed artificial limbs to look much more realistic, which is important to transradial and transhumeral amputees because they are more likely to have the artificial limb exposed. A bevy of companies are using the power of 3-D printers to bring high design to a backwater of medical devices.

In addition to new materials, the use of electronics has become very common in artificial limbs. Myoelectric limbs, which control the limbs by converting muscle movements to electrical signals, have become much more common than cable operated limbs. Myoelectric signals are picked up by electrodes, the signal gets integrated and once it exceeds a certain threshold, the prosthetic limb control signal is triggered which is why inherently, all myoelectric controls lag. Conversely, cable control is immediate and physical, and through that offers a certain degree of direct force feedback that myoelectric control does not. Computers are also used extensively in the manufacturing of limbs. Computer Aided Design and Computer Aided Manufacturing are often used to assist in the design and manufacture of artificial limbs. [88]

Most modern artificial limbs are attached to the stump of the amputee by belts and cuffs or by suction. The stump either directly fits into a socket on the prosthetic, or—more commonly today—a liner is used that then is fixed to the socket either by vacuum (suction sockets) or a pin lock. Liners are soft and by that, they can create a far better suction fit than hard sockets. Silicone liners can be obtained in standard sizes, mostly with a circular (round) cross section, but for any other stump shape, custom liners can be made. The socket is custom made to fit the residual limb and to distribute the forces of the artificial limb across the area of the stump (rather than just one small spot), which helps reduce wear on the stump. The custom socket is created by taking a plaster cast of the stump or, more commonly today, of the liner worn over the stump, and then making a mold from the plaster cast. Newer methods include laser guided measuring which can be input directly to a computer allowing for a more sophisticated design.[89]

[88] "How artificial limb is made – Background, Raw materials, The manufacturing process of artificial limb, Physical therapy, Quality control". Madehow.com. 1988-04-04. Retrieved 2010-10-03.

[89] Mamalis, AG; Ramsden, JJ; Grabchenko, AI; Lytvynov, LA; Filipenko, VA; Lavrynenko, SN (2006). "A novel concept for the manufacture of individual sapphire-metallic hip joint endoprosthesis". Journal of Biological Physics and Chemistry 6 (3): 113–117. doi:10.4024/30601.jbpc.06.03.

5.6.2 Microprocessor control

To mimic the knee's functionality during gait, microprocessor-controlled knee joints have been developed that control the flexion of the knee. Some examples are Otto Bock’s C-leg, introduced in 1997, Össur's Rheo Knee, released in 2005, the Power Knee by Össur, introduced in 2006, the Plié Knee from Freedom Innovations[90] and DAW Industries’ Self Learning Knee (SLK).[91] The idea was originally developed by Kelly James, a Canadian engineer, at the University of Alberta.[92] A microprocessor is used to interpret and analyze signals from knee-angle sensors and moment sensors. The microprocessor receives signals from its sensors to determine the type of motion being employed by the amputee. Most microprocessor controlled knee-joints are powered by a battery housed inside the prosthesis.

The sensory signals computed by the microprocessor are used to control the resistance generated by hydraulic cylinders in the knee-joint. Small valves control the amount of hydraulic fluid that can pass into and out of the cylinder, thus regulating the extension and compression of a piston connected to the upper section of the knee.[93]

The main advantage of a microprocessor-controlled prosthesis is closer approximation to an amputee’s natural gait. Some allow amputees to walk near walking speed or run. Variations in speed are also possible and are taken into account by sensors and communicated to the microprocessor, which adjusts to these changes accordingly. It also enables the amputees to walk down stairs with a step-over-step approach, rather than the one step at a time approach used with mechanical knees.[94] However, some have some significant drawbacks that impair its use. They can be susceptible to water damage and thus great care must be taken to ensure that the prosthesis remains dry.

5.6.3 Myoelectric

A myoelectric prosthesis uses electromyography signals or potentials from voluntarily contracted muscles within a person's residual limb on the surface of the skin to control the movements of the prosthesis, such as elbow flexion/extension, wrist supination/pronation (rotation) or hand opening/closing of the fingers.

Myoelectric parts were analyzed more detailed on subchapter 4.3.

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[90] "Retrieved 14 April 2009". Freedom-innovations.com. Retrieved 2010-10-03.
[91] "The SLK, The Self-Learning Knee", DAW Industries. Retrieved 16 March 2008.
[92] Marriott, Michel (2005-06-20). "Titanium and Sensors Replace Ahab's Peg Leg".The New York Times. Retrieved 2008-10-30.
[93] Pike, Alvin (May/June 1999). "The New High Tech Prosthesis". InMotion Magazine 9 (3)
[94] Martin, Craig W. (November 2003) "Otto Bock C-leg: A review of its effectiveness". WCB Evidence Based Group

5.7 More Accessible

Traditional prosthetics can cost tens of thousands of dollars, making them inaccessible to many. By using emerging technologies like 3D printing, we can cut that down to a fraction of the cost which means that these devices can reach a far broader audience.[95] Root says that the 3-D printed elements of his leg cost just $1,800, but the knee and ankle joints used in his design are specialized components that come with high-price tags. Joints that provide mechanical assistance can drive the price higher. These costs are balanced by the theoretical elimination of manual fittings and the benefits of a better looking, lighter limb. And as 3-D printers become more widespread it's possible patient's might just bootleg, well, legs.

5.7.1 Other Open-sources about prosthetics

There is currently an open design Prosthetics forum known as the "Open Prosthetics Project". The group employs collaborators and volunteers to advance Prosthetics technology while attempting to lower the costs of these necessary devices.[96]

Another open-source prosthetics design forum is called “PATCH Project”. This forum is specially focused on the development of prosthetics and tools for children in developing countries. The website is focused on storing and spreading information and improving development of open-source low-cost solutions.[97]

Open Bionics is a company that is developing open-source robotic prosthetic hands. It uses 3D printing to manufacture the devices and low-cost 3D scanners to fit them, with the aim of lowering the cost of fabricating custom prosthetics.[98]

5.8 Drawbacks

As always and in every technological innovation, there are significant drawbacks that we have to consider about 3D Printed Prosthetics. These concern mostly the energy consumption and the environmental concerns.

[95] http://www.openhandproject.org
[96] Open Prosthetics Website
[97] PATCH Project website
[98] Open Bionics

5.8.1 High energy consumption

While promoters tout the potential savings in energy that 3D printing may bring in the future, the current reality is somewhat different. Some types of 3D printers in use today are energy hogs. The Environmentally Benign Manufacturing (EBM) research group at MIT, for example, determined in 2009 that direct-metal laser-sintering (DMLS), a system of 3D printing using metal granules fused together, consumes hundreds of times more electrical power than conventional casting and machining processes. Large-scale metal processes are expected to make substantial gains in energy consumption as research and development continues, but for now, high energy use remains a significant concern.

5.8.2 Environmental concerns

Increased energy consumption plays a key role in the continuing reliance on nonrenewable energy sources such as coal and oil, causing real problems for the environment. In addition to high energy consumption, 3D printing poses a number of other environmental challenges, such as air pollution and greater reliance on plastics. While much research is needed to better understand these problems, one study from the Illinois Institute of Technology has indicated that commercial desktop 3D printers in use today emit nanoparticles of plastic that may pose a substantial health risk, and are notoriously difficult to clean up.[99]

[99] http://www.computerscienceonline.org/cutting-edge/3d-printing/

6. Patient

When an arm or other extremity is amputated or lost, a prosthetic device, or prosthesis, can play an important role in rehabilitation. For many people, an artificial limb can improve mobility and the ability to manage daily activities, as well as provide the means to stay independent.

6.0.1 Choosing and Using a Prosthesis

A number of factors are involved in choosing a prosthesis. These factors include:

- The location and level of the amputation
- The condition of the remaining limb
- Your activity level, particularly for a prosthetic leg or foot
- Your specific goals and needs

6.1 Preparing to Use a Prosthesis

Before surgery, a surgeon, a prosthetist (an expert who designs, fits, builds, and adjusts prosthesis), and a physical therapist discuss plans and goals with the person who requires amputation. Also before surgery, everyone who requires an amputation should, if possible, discuss what happens after surgery with a peer counselor who has had an amputation.

Exercises to increase muscle strength and flexibility are taught before and after amputation. The stronger and more flexible people are, the more they can do with or without their prosthesis. Some exercises depend on the type of amputation. All people need to do exercises to help reduce swelling in the residual limb and prevent tissues in the residual limb from shortening. This shortening (called a contracture) stiffens the tissues and thus limits the joint’s range of motion. As a result, using a prosthesis is more difficult.

After surgery, the residual limb must heal before a prosthesis can be worn, and swelling in the limb must be reduced before a prosthesis can be fitted for long-term use. To help reduce swelling, people are taught to apply an elastic sock (called a shrinker) or an elastic bandage over the residual limb. Wearing a shrinker or bandage also helps by shaping the residual limb and preventing irregularities that can make fitting the interface difficult. It increases circulation and makes pain in the amputated limb (phantom pain) less likely. For a while after surgery, a shrinker, bandage, or both are worn whenever the prosthesis is off. The use of a shrinker can help control swelling and reduce phantom pain. How long it is worn varies from person to person.

Until swelling in the residual limb resolves, a temporary (preparatory) prosthesis may be used. Because this prosthesis is lightweight and easy-to-use, some experts think it helps people learn to use a prosthesis more quickly. Later, this prosthesis is replaced with a permanent prosthesis, which has higher-quality components. However, with this approach, people must learn how to use two different prosthesis.

An alternative approach is to use a prosthesis with permanent components (such as a knee, foot, or hand) but with a temporary socket and frame. Because some parts remain the same, this approach may enable people to adjust to the new parts more quickly. In either case, the first socket and frame almost always need to be replaced within 4 to 6 months of amputation because the residual limb changes in shape and size.

When the prosthesis is delivered, people are taught the basics of using it:

- How to put the prosthesis on
- How to take it off
- How to walk with it
- How to care for the skin of the residual limb and the prosthesis

Training is usually continued, preferably by a team of specialists. A physical therapist provides a program of gait training as well as exercises to improve strength, flexibility, and cardiovascular fitness. An occupational therapist teaches the skills needed to do daily activities. People with lower-limb amputations learn to walk better (for example, to use stairs, walk up and down hills, and walk on uneven surfaces).

Rehabilitation for upper-limb amputations is coordinated by an occupational or physical therapist with the prosthetist. The rehabilitation consists of specific exercises designed to strengthen muscles and maintain their flexibility in the residual limb, as well as teaching the person how to use the prosthesis for daily activities.

Counseling or psychotherapy may help when people have prolonged difficulty adjusting to the loss of their limb and to prosthetic use.[100]

6.2 Pain in the Residual Limb

Pain secondary to limb amputation is common. Multiple factors may contribute to the presence and persistence of pain before and after lower limb amputation. Patients may experience immediate postoperative pain or may experience post-amputation pain including residual limb pain or phantom limb pain. In addition, patients with a lower limb amputation may have musculoskeletal pain (low back, hip, and knee pain) as a result of poor body mechanics or arthritis. Pain management strategies,

[100] http://www.merckmanuals.com/home/special-subjects/limb-prosthetics/preparing-to-use-a-prosthesis

including both pharmacological and non-pharmacological treatments, vary depending on the type and severity of pain.

Residual limb pain occurs in the part of the limb left after the amputation. This pain can be due to mechanical factors such as poor prosthetic fit, bruising of the limb, chafing, or rubbing of the skin. Pain in the residual limb can also be caused by ischemia, heterotopic[viii] ossification, or post amputation neuromas[ix].[101]

6.2.1 Phantom Pain

Many people experience phantom pain at some time. Phantom pain was experienced by 42% in one study with over one third of their respondents noting constant or daily pain. The phantom aspect is not the pain, which is real, but the location of the pain—a limb that has been amputated.). Phantom sensations, such as tingling, warmth, cold, cramping, or constriction in the missing portion of the limb, are likely to be experienced by most amputees and may be present throughout their entire life. Phantom sensation should be considered normal and treated only if it becomes disruptive to functional activities. Phantom pain is more likely if the pain before amputation was severe, lasted a long time, or if the amputation occurred as the result of trauma. Phantom pain is often more severe soon after the amputation, then decreases over time. It may, in fact, lessen or disappear when using the prosthesis. If necessary, drugs and other treatments can relieve phantom pain.

For many people, phantom pain is more common when the prosthesis is not being worn (because the limb and interface have no contact), for example, at night. The risk of having this pain is reduced if a spinal anesthetic and a general anesthetic are used during surgery. Some people experience phantom sensation, which is not painful but feels as though the amputated limb is still there.

The residual limb may be painful. If it is, the person should first check for signs of infection and skin breakdown. If pain is due to infection, the doctor should be consulted. Even if there is no obvious infection, the doctor should be consulted if pain is severe and sudden or if there is fever; these symptoms may indicate an infection also. The area may be cleaned or flushed out with a solution. Dead skin may be removed, and a bandage applied. Antibiotics and sometimes surgery may be needed.

If there is no infection or skin breakdown, massaging the residual limb sometimes relieves the pain. If massaging is ineffective, pain relievers (analgesics) can be taken. Sometimes opioid (narcotic) analgesics are prescribed. If these measures do not relieve the pain or if the person needs to take opioids for a long time, a pain management specialist may be required to supervise treatment. This treatment of pain may include using mechanical devices (such as a vibrator), ultrasound, and drugs. The drugs may include antidepressants (such as nortriptyline or desipramine) and anticonvulsants (such as gabapentin).

[101] http://cirrie.buffalo.edu/encyclopedia/en/article/251/

Sometimes pain is felt in other limbs or in the hips, spine, shoulders, or neck. This pain may occur because wearing a prosthesis makes people change the way they walk or hold their body (body alignment) or causes them to repeat movements. Regularly doing specific stretching exercises and exercises to strengthen muscles may help prevent or relieve this type of pain. A physical therapist can help design an appropriate exercise program.[102] [103]

6.3 Psychology of the patients

The loss of a limb can have a considerable psychological impact. Many people who have had an amputation report feeling emotions such as grief and bereavement, similar to experiencing the death of a loved one. Coming to terms with the psychological impact of an amputation is therefore often as important as coping with the physical demands. Having an amputation can have a considerable psychological impact for three main reasons:

- you have to cope with the loss of sensation from your amputated limb
- you have to cope with the loss of function from your amputated limb
- your sense of body image, and other people's perception of your body image, has changed

It's common to experience negative thoughts and emotions after an amputation. This is especially true in people who had an emergency amputation, as they did not have time to mentally prepare themselves for the effects of surgery. Common negative emotions and thoughts experienced by people after an amputation include:

- depression
- anxiety
- denial (refusing to accept that they need to make changes, such as having physiotherapy, to adapt to life with an amputation)
- grief
- feeling suicidal

People who have had an amputation due to trauma (especially members of the armed forces injured while serving in Iraq or Afghanistan) also have an increased risk of developing post-traumatic stress disorder (PTSD). This is when a person experiences a number of unpleasant symptoms after a traumatic event, such as "reliving" the event and feeling constantly anxious. [104]

[102] http://www.nationalamputation.org
[103] http://www.msdmanuals.com/professional/special-subjects/limb-prosthetics/pain-in-the-residual-limb
[104] http://www.nhs.uk/Conditions/Amputation/Pages/Complications.aspx

6.4 Social Inclusion

Social integration can be seen as a dynamic and structured process in which all members participate in dialogue to achieve and maintain peaceful social relations. Social integration does not mean forced assimilation.

Social integration is focused on the need to move toward a safe, stable and just society by mending conditions of social disintegration and social exclusion - social fragmentation, exclusion and polarization; and by expanding and strengthening conditions of social integration - towards peaceful social relations of coexistence, collaboration and cohesion.[105]

6.4.1 Prosthetic enhancement

In addition to the standard artificial limb for everyday use, many amputees or congenital patients have special limbs and devices to aid in the participation of sports and recreational activities.

Within science fiction, and, more recently, within the scientific community, there has been consideration given to using advanced prosthesis to replace healthy body parts with artificial mechanisms and systems to improve function. The morality and desirability of such technologies are being debated by transhumanists, other ethicists, and others in general.[106] [107]Body parts such as legs, arms, hands, feet, and others can be replaced.

The first experiment with a healthy individual appears to have been that by the British scientist Kevin Warwick. In 2002, an implant was interfaced directly into Warwick's nervous system. The electrode array, which contained around a hundred electrodes, was placed in the median nerve. The signals produced were detailed enough that a robot arm was able to mimic the actions of Warwick's own arm and provide a form of touch feedback again via the implant.[108]

[105] "PeaceDialogue." UN News Center. UN, n.d. Web. 02 Jan. 2015.
[106] Enhancements, Oxford Uehiro Centre for Practical Ethics
[107] Caplan A., Elliott C. Is It Ethical to Use Enhancement Technologies to Make Us Better than Well?
[108] Warwick K, Gasson M, Hutt B, Goodhew I, Kyberd P, Andrews B, Teddy P, Shad A (2003). "The Application of Implant Technology for Cybernetic Systems". Archives of Neurology 60 (10): 1369–1373. doi:10.1001/archneur.60.10.1369

7. MAI and Prosthetics

Coming close to the end, I would like to recap some key points that will help me make an argument of my following proposition. In this chapter I will try to argue about the Master Program I am attending and how in my opinion there should be a direction on Prosthetics. The ideal, in my point of view, would be the students to have the option whether they want to follow this direction, as I think that is a very important field, where Artificial Intelligence can play a crucial role. Of course the other subjects that are available to chose from the Master's Syllabus, are also important gaining knowledge on Artificial Intelligence. But since I have chosen to attend this program, in order to learn about Prosthetics also, I was in a way, disappointed.

7.1 Importance of inserting this direction

Artificial Intelligence, as it was proven in the whole thesis, is a very important part of prosthetic limbs and progressing the field even more. In my opinion, the main reason of following, devoting and serving a career, would be to make our world a better place for us and for the fellowmen. Based on that, I believe that Assistive Technology and Prosthetic limbs are two fields, that our knowledge from this Master, can be helped and developed.

As we saw at chapter two, three and four there are main ways Artificial Intelligence and Prosthetics can benefit from each other. In that way, there is a real evolution in technology while at the same time, this union is making people's lives easier, better and hopeful . Patients may maximize their functional abilities, rehabilitation potential, and regain independent and product lifestyles.

7.2 More related courses are needed

At the Master of Artificial Intelligence, held on Universitat Politecnica de Catalunya, there were some subjects related to this field. For example, Cooperative Robotics, Cognitive Interaction with Robots, Professional Practice in Artificial Intelligence and Human-Computer Interaction. Nevertheless, there was no reference on Prosthetic limbs, but either the subject was focusing on Robots, either on Assistive Technology. Of course, both of these fields were very helpful and for a student like me that is interested on Prosthetic limbs, were also the most related courses.

Therefore, in my opinion, there should be two or three more courses, that would even make an introduction on Prosthetic limbs and subsequently get dipper on this area. I feel many colleagues would be interested in this field and why not, since Universitat Politecnica de Catalunya is already pioneer on many technological developments, could also make a difference in Europe constructing and programming a new model of Prosthetic limb. 3D Printers would also help in decreasing the cost combined with knowledge that would be gained from the Master Program.

Conclusively, I strongly believe it is necessary and I suggest to the authorized people, to add this field of knowledge to our Master degree.

8. Future Work - Proposal

As we saw at the chapter referring to the 3D-Printing the cost of an artificial limb can be much lower than the one of the constructing companies like Ottobock and Össur. As I already mentioned this is very important, as a prosthetic limb should be accessible and affordable to anyone. Hopefully, there are several helpful open sources like the "*Open Prosthetic Project*", where anyone can find the main coding that would help start programming a prosthetic limb made by a 3D Printer. Already, there are many researching groups around the world that work on developing the technology on prosthetics.

We expect a big progress on microprocessors and sensors used in 3D Printed prosthetics, as well as inserting accelerators and even gyroscopes to lower prosthetic limbs. That would make no difference from Rheo Knee 3 by Össur. Nevertheless, this will constrain the big companies, that now have the monopoly, to decrease the cost of their products and make these products more affordable to anyone.

A progress on this field is necessary, since the cost of a prosthetic limb would decrease and in parallel, the amputee using a prosthetic limb made by a 3D Printer wouldn't be unprivileged, concerning the technology used, comparing to an amputee using a prosthetic limb costing over 60,000$.

Conclusively, we expect a forthcoming evolution on this area, combining the materials we already have with the knowledge, as well as the consciousness for the fellow human. In my point of view, this would be a promising society for everyone regarding to the field analyzed on this thesis. And we, for our part as scientists, we have a duty to work and labor for a better future of this society.

9. Conclusions

Limb loss is one of the most physically and psychologically devastating events that can happen to a person. Thankfully, the technology has developed a lot the past decades, in order to serve people's needs. One of the main ways is the entrance of Artificial Intelligence in the field of Prosthetic limbs. In this thesis, I tried to do a bibliographic review of the Prosthetics evolution and how AI has helped a lot this area. Nowadays and in the future, there would be many options for the amputees to chose, with different costs, possibilities and features.

For now, there are some drawbacks on really developed Prosthetic limbs, like the cost. That makes the Prosthetic limb affordable not to anyone. 3D Printing has involved and positively participated in the field of Prosthetics, serving mostly developing countries and people who cannot afford the most advanced models. But, as we saw the technology imported in 3D printed prosthetic limbs, is quite advanced and nevertheless promising for the future, as the young scientists and engineers that involve and show interest this field are increasing.

Technology is always developing and moving forward, even in short amounts. This opens many possibilities for bionic limbs to become better working, more accurate and more efficiently for those in need. Therefore, in the future the availability of prosthetics that could change a person's life could become more readily available or less costly. The technology that controls the limb will always be changing and developing to figure out the best and least intrusive way to allow control. Also, I am optimistic about the future researches that would find how to allow a person to assimilate into their new life with a new prosthetic and not make the advancement too noticeable.

Although many challenges remain and advances will be incremental, researchers and engineers are optimistic that one day the integration of technology that enables amputees to have a normal life. Either with a bionic limb that would communicate with the best accuracy with the brain, or through the further development of 3D printing, which would enable anyone, with low cost to embody an artificial limb, programmed smart enough to serve the user in the daily needs.

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[i] Osseointegration refers to a direct structural and functional connection between ordered, living bone and the surface of a load-carrying implant. Currently, an implant is considered as osseointegrated when there is no progressive relative movement between the implant and the bone with which it has direct contact.

[ii] Reinnervation is the restoration, either spontaneously or by surgical grafting, of nerve supply to a part of the body from which it has been lost.

[iii] The magnetorheologic (MR) fluid actuator that continuously measures the flow of magnetized fluid through tiny rotary blades - within the prosthetic's sleek, lightweight aluminum shell.

[iv] Is the amputation of the lower leg between the ankle and the knee. Called also below-knee (B-K) amputation

[v] Dorsiflexion and plantar flexion refers to extension or flexion of the foot at the ankle. These terms refer to flexion between the foot and the body's dorsal surface, considered the front of the leg, and flexion between the foot and the body's plantar surface, considered the back of the leg. These terms are used to resolve confusion, as

technically extension of the joint refers to dorsiflexion, which could be considered counter-intuitive as the motion reduces the angle between the foot and the leg. Dorsiflexion where the toes are brought closer to the shin. This decreases the angle between the dorsum of the foot and the leg. For example, when walking on the heels the ankle is described as dorsiflexion. Plantar flexion is the movement which decreases the angle between the sole of the foot and the back of the leg. For example, the movement when depressing a car pedal or standing on the tiptoes can be described as plantar flexion.

[vi] Preflexes are the latent capacities in the musculoskeletal system that auto-stabilize movements through the use of the nonlinear visco-elastic properties of muscles when they contract. The term "preflex" for such a zero-delay, intrinsic feedback loop was coined by Loeb. Unlike stabilization methods using neurons such as reflexes and higher brain control, it happens with minimal time delay. Its chief disadvantage is that it works only to stabilize the main movements of the musculoskeletal system.

[vii]Stereolithography (SLA or SL) is a form of additive manufacturing technology used for creating models, prototypes, patterns, and production parts in a layer by layer fashion using photopolymerization, a process by which light causes chains of molecules to link together, forming polymers.

[viii] Occurring in an abnormal place.

[ix] A tumor or mass growing from a nerve and usually consisting of nerve fibers.