



University of Technology
Materials Engineering
Department

Polymers and
Petrochemicals Branch
4th Stage – Morning
Study

9/8/2020

Materials Selection for Prosthesis Leg

Material Selection – First Course

المادة: إختيار المواد – الكورس الأول

Maryam Maher Jameel Nedham

تم الإعداد من قبل: مريم ماهر جميل نظام

Supervised by: Dr. Ahmed Ameen

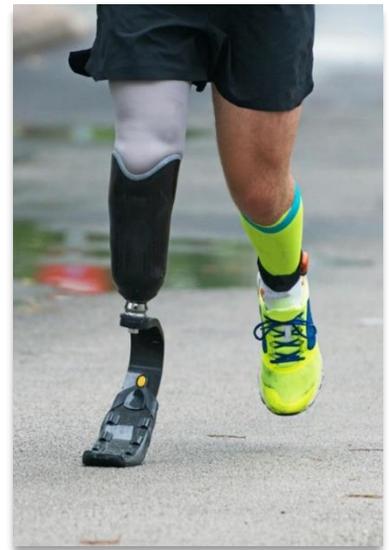
تم الإشراف من قبل: د. أحمد عميد

INTRODUCTION

The importance of prosthetic gadgets and appliances is increasing day by day in medical and engineering areas, nowadays, most parts of the body are replaceable using a prosthetic. Prosthetics are a branch of the science of bio-mechatronics which deals with the use of mechanical gadgets or devices with human bones, muscles, skeleton and nervous system to improve or restore control over muscles that was lost by an accident, illness or defect. **Designing prosthetics is a complex process** because every part of it is customized for each consumer's specific requirements. Prosthetics help people perform daily tasks that they normally cannot because of their disabilities, as well as providing better life quality. **Several factors** like a person's **1) size, 2) weight, 3) lifestyle and 4) amputation affect the design of prosthetics**, therefore, the materials and designs for prosthetics vary because each person's needs are different.

When creating a new prosthetic device, the designer must take into account **the material and the main load bearing structure**. A **lightweight strong prosthetic** is necessary. The aesthetic aspect is also important and it needs to be somewhat waterproof.

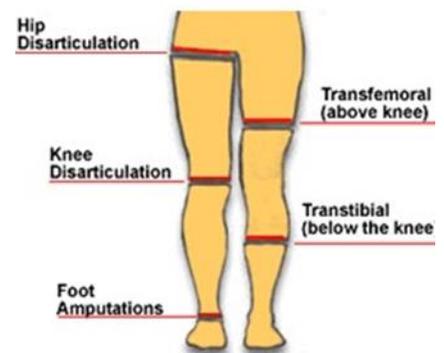
In the 20th century vast improvements were achieved in the technology of making prosthetics. **Plastics** are being used to manufacture strong and lightweight devices compared to those in the past that were made of iron or wood etc., the use of plastics and better printing and coloring techniques helped create realistic human skin-like legs. The most promising advancement in this field is the creation of limbs that work with **"Myoelectricity"**, which means that those devices use electrical signals from the user's muscles to move limbs. Model design of prosthetic legs was improved by using computers and **CAD/CAM** to design prosthetics for amputees.



KINDS OF ARTIFICIAL LOWER LIMBS

There are two key categories of prosthetic legs (lower limb prosthesis) **based on the amputation type**:

- 1. Transtibial prosthesis:** for amputations splitting the tibia bone or a hereditary abnormality resulting in the lack of tibia bone in the leg. This type is also known as **below the knee prosthesis (BK)**, in this type, only the lower limb of the patient needs to be replaced. These devices are composed of a foot, shank and a socket. **The socket's function** is to protect the remaining limb, in addition to helping the patient transfer their weight to the ground using the prosthesis successfully. **The suspension system** in the prosthetic makes sure that the socket stays in place and surrounds the remaining limb.
- 2. Transfemoral prosthesis:** for amputations splitting the femur bone or a hereditary abnormality resulting in the lack of femur bone in the leg. This type is known as **above the knee prosthesis (AK)**. These are more complex since a knee system needs to be built-in. This type consists of a foot, an ankle joint, a socket and a knee system. Nowadays, these prostheses neglect using an upper shank attached between the knee and socket, and instead the socket is connected but rather the knee is connected to the socket at once and the device only contains a lower shank, the lower shank is attached from the knee to the ankle. Trans-femoral prostheses **require swing control to maintain a smooth normal gait cycle**.



Different types of amputations in the lower limbs.

*There are other types of amputations in the lower limb that are less common and they include: hip disarticulations (when an amputation or an abnormality occurs

near the hip joint), knee disarticulations (refers to the disarticulation of the femur from the tibia across the knee), partial foot and ankle disarticulation.

THE COMPONENTS AND ARCHITECTURE OF AN ARTIFICIAL LOWER LIMB

The lower limb prosthetic device is composed of the following units:

- **Socket unit:** it comprises of socket, socket adapters and liner.
- **Double adapter:** it consists of a double ended adapter that is used to connect pyramid adapters, it could be made for males or females, it also joins the knee and socket in transfemoral prosthetics, and can be used in place of a pylon in both types of prosthetics.
- **Knee unit** (used only in TF prosthetics as mentioned earlier): it includes a system composed of a prosthetic knee and its adapters.
- **Tube unit:** consists of a joining pylon and tube adapters.
- **Foot unit:** this system comprises of an artificial foot, heel and foot adapters. Prosthetic feet are classified into the following:

1- Rigid feet that have no ground adaptation; Classified into:

- Foam rigid conventional foot made with a degree of synthetic foam and wood, which allows flexibility of the foot's frontal part.
- Solid Ankle Cushioned Heel (SACH).
- Rigid conventional foot made from wood.

2- Mono-axis: feet that have a single axis of ground adaptation; Classified into:

- Has a single-axis: it is a SACH foot with an ankle joint.
- Low energy: this type is able to store and release a low amount of energy, usually made with carbon fibers.
- Consists of 3-foils: which is a foot made with 3 foils of carbon fiber, that can store and release a medium amount of energy.
- Has a heel pad: a foot with a medium energy return and a cushioning heel pad.
- Consists of 3- points: a foot with 3 points that provide support when stepping on the ground.
- High energy: which is a type of feet that can deposit and release a high amount of energy.

3- Multi-axis: feet that possess multiple axes of ground adaptation; Classified into:

- C-spring: feet that contain a "C" shaped spring under the joint of the ankle.
- Sandwich: this type is built of two foils of carbon fiber and a softer component in the middle.

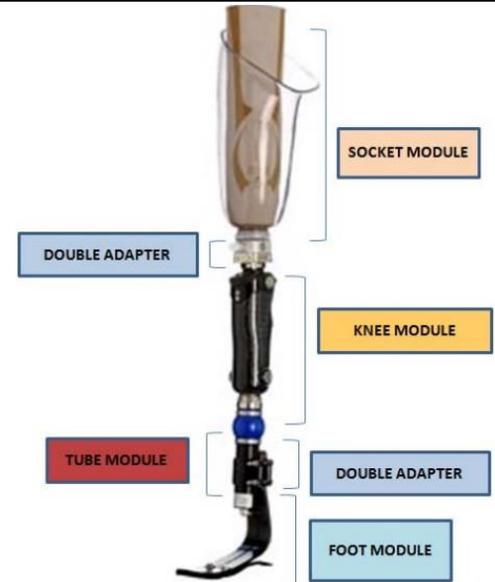
***Ground adaptation** means the difficulties that the patient needs to overcome while walking, this includes **a**-slopes, **b**-different types of grounds and **c**-limits regarding floors.

PROSTHETIC KNEES ARE CLASSIFIED INTO THE FOLLOWING:

1- **Fixed:** in which the knee's center of rotation is fixed during walking and can be manually unlocked, for example, when the person has to sit down.

2- **Monocentric:** in which the knees have a single center of rotation, that is used for their function in hydraulic, pneumatic, friction and self-brake.

The components that make up an artificial leg.



3-**Polycentric**: in which the knees have multiple centers of rotation also used for hydraulic, pneumatic, friction and self-brake.

FUNCTIONS OF THE PART AND ITS USES

Artificial lower limbs can replace lost body parts of the amputee. Amputation of a person's leg may occur due to accidents or diseases, **prosthetics are required for many reasons**, such as accidents, hereditary defects, and diseases. A person with a congenital deformity and who is born without a limb or with a damaged limb needs a prosthetic. Diseases like cancer, infection and vascular illnesses are the main diseases that cause amputation. Accidents from vehicles, workplace and war related accidents are also main causes of amputation. Therefore, *the need for prosthetic legs is increasing*. Artificial legs are made to support the amputee, as well as equally meet the performance level of original human limbs. Nowadays, a prosthetic helps amputees achieve their day to day tasks.

The main function of the prosthetic lies in mimicking a human's natural leg movement, and when a prosthetic leg is used there is no need to use a wheel chair, hence, providing independence and a more regular life for children and adults.

DESIGN REQUIREMENTS AND MATERIALS CURRENTLY BEING USED IN MAKING PROSTHETIC LEGS

The **selection of an artificial leg** is done by considering the properties such as:

- Compressive strength
- Torsional strength
- Tensile strength
- Shear strength
- Ability to store energy
- Specific density
- Stiffness
- Fatigue resistance
- Damping (Shock absorption)
- Creep
- Fracture toughness
- Biocompatibility
- Yield stress

When designing a prosthetic leg, the following **requirements** should be met as much as possible:

- Low density
- High tensile strength
- High compressive strength
- High corrosion resistance
- Availability
- Easy to replace, easy to put on and off
- High shear strength
- Flexibility
- Durability
- Cost efficiency
- Easily repaired
- Adjustable

Because the human body is changing over time, because of factors like change in body weight, height or growth etc., prosthetic devices must be replaced or adjusted constantly. **Replacing the prosthetic limbs may be high-priced if the materials used are expensive.**

The prosthetic leg must bear the static and dynamic loads created by a person while he/she is walking, low cost, adjustability and interchangeability, which means that the leg can function as transtibial (Below the knee) or transfemoral (Above the knee), in this flexible construction, the patient can change between the two types simply by changing where the socket is connected (either the upper or lower shank. This will decide if a knee joint is incorporated in the prosthetic leg or not.

Design objectives:

1. The legs structure needs to be composed of modules to allow for interchangeability of components for easy use as the person grows (especially children), thus, they can keep the prosthetic for a longer time.
2. The design should be easily adjustable.
3. The structure must be strong enough to withstand a weight of 100 kg.

4. The prosthetic must be lightweight so as to not delay and hold back the patient who might already have weak muscles in the remaining limb.
5. The prosthetic needs to be suitable for lifestyles of younger and older people.

Important parameters controlling material choice are processability, easy assembly, durability and cost. Low cost artificial legs are currently being manufactured from fiber glass owing to its high modulus of elasticity, easy manufacturing and low cost. Simple designs use materials like wood and recycled water bottles to reduce expenses. **Thermoplastic materials** are widely used because of their *sustainability and easy processing*, they can be recycled, melted, recycled and remolded after production. This is beneficial in case of defects or problems with the initial design or fabrication method, the plastic can be reheated then remolded.

Materials that are commonly being used are Polypropylene Carbon fiber, Kevlar, reinforced Carbon fiber because they match the required mechanical and physical properties.

1-Socket materials: The socket is composed of two parts, the rigid socket and the soft socket liner, **rigid sockets** must be able to distribute load produced during the gait cycle on the remaining limb, **soft socket liners** protect and surround the remaining limb, they provide movement freedom, transferring of loads, appropriate control and equal pressure on the exterior of the limb. **The rigid socket** is made from plastics that are solid polymers in their final shape. Tensile and compressive stresses are produced due to pressure from gait and weight; therefore, the prosthetic must have enough strength to bear stress, **high strength materials** enhance the suspension by **decreasing slipping during walking** (gait). Stiffness of the material selected depends on the residual limb state, patients with little bone end covering benefit from a coating with lower stiffness, while others with soft tissue can attain more control by materials with higher stiffness. Sockets should allow damping of stresses caused by changes in volume. Rigid sockets are made from thermoplastic or thermostable polymers, **thermostable polymers** remain hard and rigid even at high temperatures, and cannot be melted with heat, thus, their production is difficult, **thermoplastics** possess high molecular weight and can be molded with heat, some of those are LDPE, HDPE, and Polypropylene (PP). Polyethylene is known for processability, low weight and flexibility, so it's used in prosthetics that require flexibility. PP is lighter than all other plastics, possesses high stiffness, tensile strength and hardness, but it can easily be deformed by heat, PP is currently being used in making legs with high rigidity. Experiments have shown the effectiveness of sockets made of epoxy resins reinforced with glass fiber and 0.3% carbon nanoparticles, this was found to **increase thermal conductivity and flexural strength and reduce weight by a great amount** compared to resins with no reinforcement. Fibers are suitable because they increase mechanical properties of the prosthetic, for example, Aramid fibers that are even more resistant than aluminum and steel, but they are not quite compatible with a PP matrix, therefore, glass fibers can be more compatible with the PP matrix but the mechanical performance is compromised. Carbon fibers were found to increase mechanical properties like resistance and stiffness (35000 Psi) while reducing the weight.

Soft Socket liners need to be able to absorb shock and therefore, **produced from foams** to provide comfort for the patient, urethane foams are extensively used because they vary in texture and shape. PE, PU and latex foams like Pelite are also used due to their ability to recover from stress and low weight. Prosthetic liners are made from silicone gels that have high PDMS fluid content which allows for **extension under load**, but they have lower mechanical properties than liners made from Silicone elastomers, those elastomers have less free liquid and allow for less extension. It was found that using Silicone lining materials reduced skin abrasion and diseases, as

well as better control over the leg, owing to the shape memory effect and hardness of Silicone. Composites have provided the best chemical, mechanical and physical properties for being used in prosthetics but are quite expensive.

In conclusion, polymers structures allow for attaining a wide range of properties and low weight, but they do not match the best performance/durability requirements, materials like carbon fiber have better properties but with higher production expenses.

2-Pylon materials: Lightweight metals like aluminum and titanium, steel and their alloys are widely used in the making of pylons in a prosthetic leg, some **parameters decide material choice of a pylon**, the pylon must be comfortable, durable, rigid and lightweight to allow the ability to move the artificial leg forward while reducing subjected stress on the knee. When the leg is light it can swing easily forward, thus, the stress on the knee will be reduced. It's crucial that the pylon tolerates dynamic loading caused by the foot during walking (gait cycle) that results in torsional and bending stress on the pylon. **Therefore, our aim is to create a pylon with the smallest mass but enough mass to endure stresses on the pylon.** (Fig 1)

$$\text{Bending stress} = \sigma^{(1/2)}/\rho, \text{ Torsional stress} = \tau^{(2/3)}/\rho$$

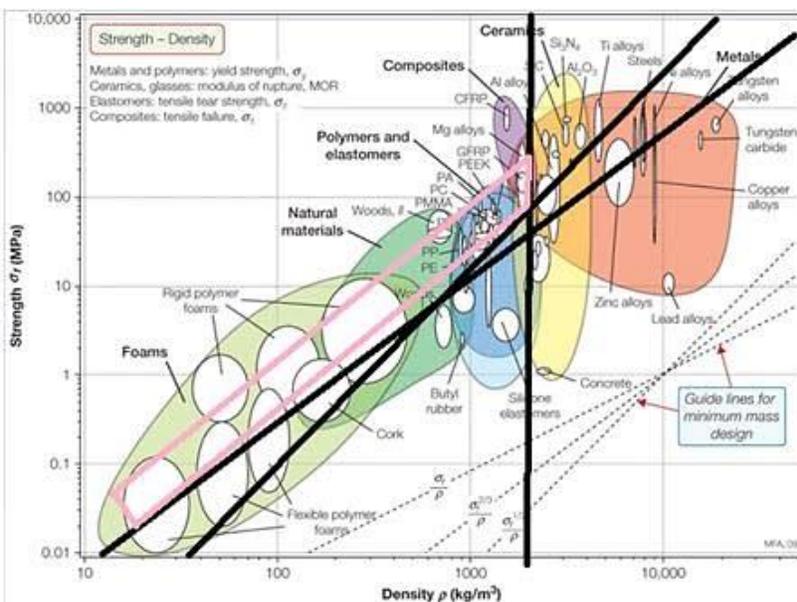


Figure 1: Strength of the pylon needs to be 3 times its weight

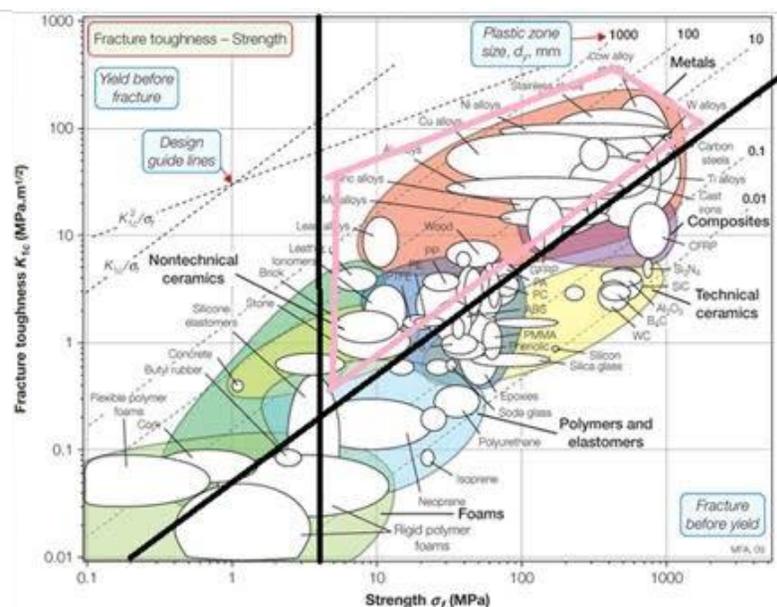


Figure 2: The pylon should not crack under load and have ductility

Taking into account that the pylons needs to have high fracture toughness so that they don't crack under load, it is important to **reduce or minimize the crack length** of the pylon and make it **ductile enough** to remain stable. (Figure 2). Suitable pylon materials from the chart above are **metals, metal alloys, carbon steels, PE, PP, PTFE, and wood.**

The design of the pylon mustn't be very costly as it needs to be available for most people, therefore, the cost to volume ratio needs to be reduced, without compromising the strength necessary to endure stress. (Figure 3). **The best choices appearing from the chart are:** Aluminum and Magnesium alloys, such metal alloys are widely

used as materials for pylons as well as PE (Polyethylene), also HDPE can very much withstand stress while having low cost.

3-Foot materials: Foot materials used in foot manufacturing need to possess flexibility to absorb shock and relieve shear stress caused by walking, they also need to be strong enough to handle the weight of the patient and the artificial leg. Urethanes are known to have to have high capacity for bearing loads, as well as better tear and abrasion resistance than elastomers and rubbers. Therefore, Polyurethane is the most suitable material for this part because it also prevents slippage, when mixed with the durability and toughness of metals it gives excellent results. It was found that blending Carbon fiber with fiberglass and PMMA enhances mechanical properties, improves durability and decreases costs. When Kevlar fibers were blended with Carbon fiber the material displayed great enhancement in mechanical properties, reduce of weight, tensile strength, high stiffness and compression strength, while maintaining cost efficiency and being flexible.

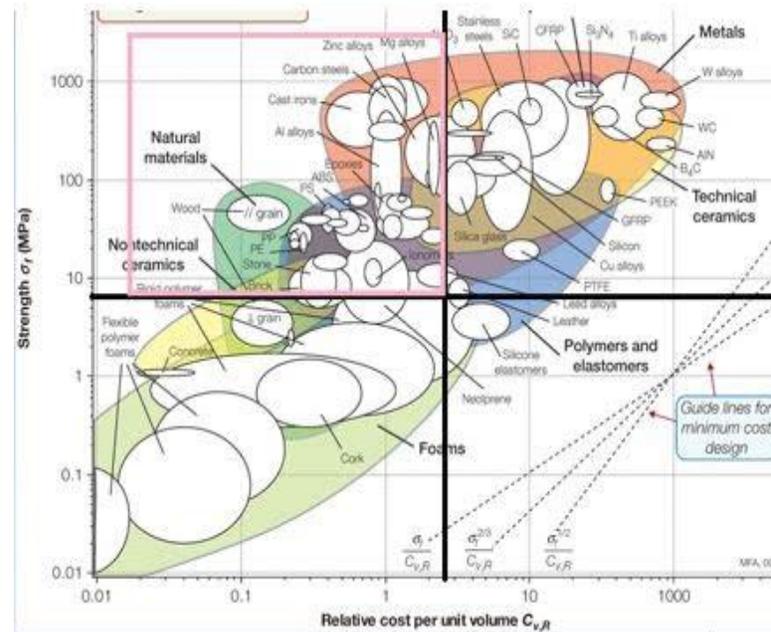


Figure 3: The pylon materials need to be affordable and low cost while still having the required strength

MANUFACTURING PROCESS OF THE PART

Artificial legs are first prescribed by a doctor after viewing the patient, the requirements and prescription are transferred to a prosthetist, the patient then gets his artificial leg installed. This is why prosthetics are custom made based on each person's disability and needs, and not mass produced, some parts like the socket are custom made but other components like pylons and feet are produced in factories. In some cases, all parts are custom made but that process is costly. The manufacturing of prosthetics is done in 3 stages:

1-First stage: An impression is taken by the prosthetist of the patient's remaining limb to achieve accurate details in order to design a leg that is similarly comfortable like the original one. The number, size and location of remaining tendons and bones in the residual limb is then defined by measuring the lengths of different body parts, upon obtaining results from measurement and using the impression, a plaster cast of the stump is then performed. The plaster cast is usually made with Plaster of Paris, because of its ability to give exact details and it can dry fast. The plaster cast will produce an identical representation of the stump (positive mold).

2-Second stage: In this stage, the socket is made by heating a thermoplastic material in an oven and then layered on top of the positive stump mold by vacuum forming, the hot clear sheet of plastic is put over the mold inside a vacuum chamber. If the sheet solidifies mid process it's reheated. Using vacuum, the air between the mold and sheet in the vacuum action forces the thermoplastic sheet into the identical form of the mold. This sheet represents a testing socket that is crystal clear to help the prosthetist clearly see if it fits the patient or not. This test socket is used as a prototype to try it on the patient's leg and see if it sits in place well. The prosthetist examines how comfortable the patient is while walking with the test socket by noticing his walking gait. In case of any discomfort, the required adjustments are performed on the leg and it's re-made. This is where the properties of thermoplastics come in handy, as it can be remolded by heating to a perfect form. A final socket is then produced, it is commonly made of PP, therefore it can be made in the same way by vacuum forming.

3-Third stage: The soft lining of the socket (plastic foam) are produced by plastic forming procedures, such as injection molding, vacuum forming or extrusion. Pylons are made from metals like Aluminum, Steel or Titanium, they can be manufactured by die casting in which the metal is melted and pushed into a steel mold to create the desired shape. The wooden parts (if wood is being used) are sawed, planed, drilled and polished into place. All of the parts are assembled by laminating, using adhesives or bolts etc. Screwdrivers and a wrench are used to put together the final prosthetic is by a specialist. The artificial leg is then permanently attached to the residual limb.

REFERENCES

1. **Materials of Prosthetic Limbs** . Mota, Anissa (California State Polytechnic University, Pomona, 2017-06-15).
2. Nadia, Shasmin Hanie. **“Development of a new pylon material in transtibial prosthesis”** / Hanie Nadia Shasmin.” (2012).
3. Colombo, G., Gabbiadini, S., Regazzoni, D., & Rizzi, C. (2011). **“Design Procedure and Rules to Configure Lower Limb Prosthesis”**. Volume 2: 31st *Computers and Information in Engineering Conference, Parts A and B*.
4. Sansoni, Stefania. (2015). **“A new design system of below-limb prostheses: The role of a visual prosthetic designer”**.
5. Me, R.C., Ibrahim, R., & Tahir, P.M. (2012). **“Natural based biocomposite material for prosthetic socket fabrication”**.
6. Virgil Faulkner, C.P.O. Martha Field, M.S., John, W., Egan, M.S. Norman, G., Gall, M.D. (1986). **“Evaluation of High Strength Materials for Prostheses”**. *Orthotics and Prosthetics*, Vol 40, 44 – 58.
7. Quintero-Quiroz, Catalina, & Pérez, Vera Zasúlich. (2019). **“Materials for lower limb prosthetic and orthotic interfaces and sockets: Evolution and associated skin problems”**. *Revista de la Facultad de Medicina*, 67(1), 117-125.
8. Walke, K. (2017). **“Mechanical Properties of Materials Used for Prosthetic Foot: A Review”**. *IOSR Journal of Mechanical and Civil Engineering*, 17, 61-65.
9. Thilina H. Weerakkody, Thilina Dulantha Lalitharatne, R. A. R. C. Gopura, **“Adaptive Foot in Lower-Limb Prostheses”**, *Journal of Robotics*, vol. 2017, 1-15.
10. B. L. Klasson, **“Carbon fiber and fibril lamination in prosthetics and orthotics: some basic theory and practical advice for the practitioner ”**, *Prosthetics and Orthotics International*, Vol. 19, 1995, 74-91.