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From Metals to Composite Materials: A Comprehensive Review of Materials Used in Prosthetic Limb Manufacturing

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Abstract:

The field of prosthetics has witnessed significant and extensive development with the advancement in the use of materials for prosthetic limbs. In the past, prosthetic limbs were made of wood, but the industry evolved to include metals and their alloys. However, the limitations of these materials, prompted researchers in the field of materials science to seek more advanced and flexible alternatives. Recently, there has been a shift towards using polymeric, composite materials, and fibers such as carbon and glass fibers due to their desirable properties, such as lightweight, strength for fibers, ease of shaping, and flexibility regards to polymers, which have made life easier for prosthetic users. This review showcases the developments in the manufacturing of prosthetic limbs in terms of the materials used and their suitability for each part of the lower limb prosthesis.

Keywords: Prosthetic limb manufacturing, Metal, Polymer, Composite material, Carbon fiber, Glass fiber

Introduction

The first prosthetic limb was installed in ancient Egypt in 218 BC. At that time, it was made of simple wood or metal and was used to replace missing limbs. For example, among ancient Egyptian artifacts, there is a statue of a woman wearing a prosthetic limb made of wood and leather in the shape of a toe, as shown in figure 1 (a) below [1].

The development of prosthetic limbs began in the Middle Ages during the wars, when it evolved into the use of materials such as metal and wood. In the 16th century, the Swiss physician Pierre Frank conducted the first attempts to manufacture advanced prosthetic limbs using metal parts, which helped further develop this field. A prosthetic limb can be defined as an artificial device used to replace a amputated foot in the human body, such as the shin or foot, due to injury, disease, or a congenital condition. Prosthetic limbs vary in design and materials, with some being simple, performing basic functions, while others are advanced and incorporate modern technologies such as sensors and artificial intelligence, allowing for more precise control and natural movement as shown in figure1 (b). The materials used in prosthetics are carbon composite, titanium, stainless steel, polypropylene, polyethylene, silicone, synthetic leather, aluminum, and metals. Regarding their uses, manufacture also varied, ranging from wood and metals [2,3].

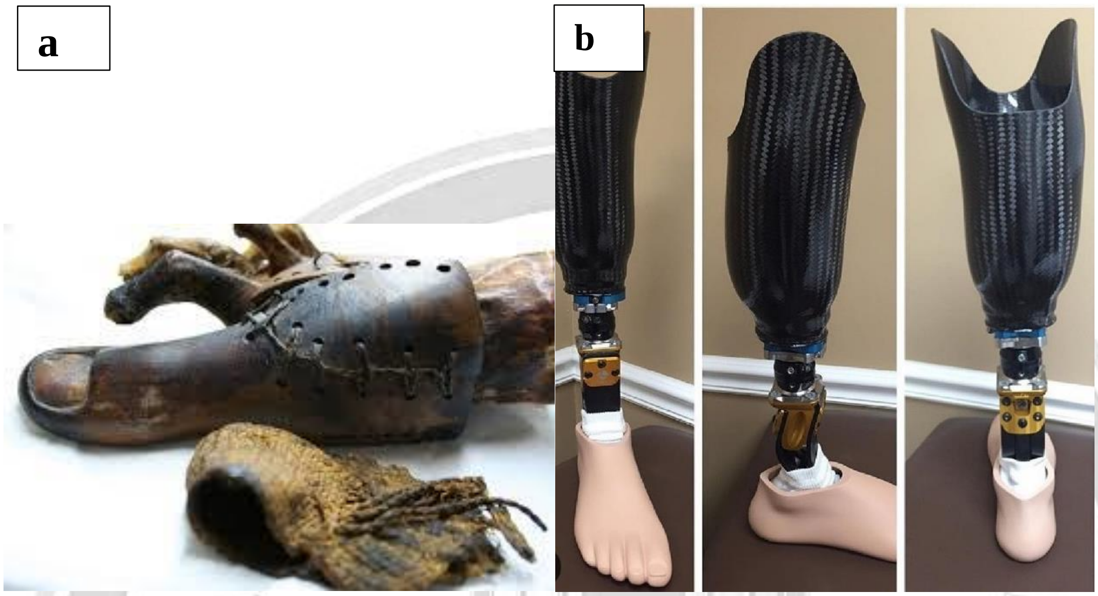

Fig.1 prosthetic foot a) ancient prosthetic foot made of wooden[4] b) modern prosthetic foot made from carbon fiber

A prosthetic limb consists of parts divided into...

1. Socket: A socket connects the remaining limb (stump) and a prosthetic component. This unique sleeve is designed to fit tightly around the remaining limb's end. It forms a suction seal, allowing the prosthesis to distribute an amputee's weight and aid their motion, thereby making it smooth and painless. [5].Sockets are created from material such as acrylic, carbon fiber, fiberglass, polypropylene, silicone, and gel [6].
2. Adapter: A component used to connect or connect different parts in prosthetic limbs or other devices. Adapters can be designed to connect structural components, joints, or tubes in prosthetic limbs, or to connect different components together. The materials used to make adapters depend on the desired function, but in general, they must be strong, flexible, corrosion-resistant, and able to withstand various conditions. Adapters are made from stainless steel, aluminum, polyamide, polypropylene, silicone, titanium, and engineering plastics [7].
3. Pylon: An crucial component of a lower limb prosthetic, it gives assistance for walking and rehabilitation for individuals who have had their lower limbs amputated. Traditionally, prosthetic pylons are hollow tubes made of aluminum, titanium, and stainless steel alloys, carbon fiber, engineering plastics, and fiberglass [8].
4. The joint: The joints in prosthetic limbs allow the user to perform various movements, such as walking, running, or even carrying objects. The materials used in their manufacture include stainless steel, aluminum, titanium, polyamide, carbon fiber, and silicone [9].

5. Prosthetic limb liner: This is an inner layer placed inside the socket of the prosthetic limb. This liner is designed to provide comfort and support to the user, while also reducing pressure and friction between the skin and the hard materials of the prosthetic limb. The liner is an important component that affects the comfort and overall fit of the prosthetic limb. It is made from materials such as silicone, polyurethane, synthetic leather, gels, and elastic materials [10].
6. Prosthetic foot: This part mimics the function of the natural foot. The materials used in the foot include stainless steel, aluminum, titanium, plastics, carbon fiber, silicone, and hydraulic or pneumatic materials [11] .

Material used in Prosthetic Limb Manufacturing

Depending on the basic classified of material can classify into four type metal, polymer, ceramic, composite material. The most material used in prosthetic manufacturing are metal, polymer, composite material.

1. Metals in Prosthetic Limb

They are widely used in the manufacture of prosthetic limbs due to their ability to provide support and durability. Metals have unique chemical and physical properties. In prosthetic limbs, metals are used according to the user's needs, such as durability, strength, and light weight [12,13].

Titanium and Its alloys: It is a lightweight, strong, and corrosion-resistant metal, characterized by its high resistance to rust and chemical reactions. Physically can describe as silvery-gray, light, powerful metallic metal that is mostly utilized in alloys, refractory materials, pigments, and dental and medical equipment. It is derived from rutile and ilmenite. It considered one of the strongest and lightest metals. It suitable for prosthetic limbs that require light weight. It is used in supporting structures and parts that require stability and strength [13].

Fig 2. Titanium Prosthetic leg [13]

Table 1. Titanium and Titanium alloy [13]

Typical composition of Commercially Pure Titanium

Material	Titanium	Iron	Oxygen	Carbon	Nitrogen	Hydrogen
Grade 2	Bal.	<0.3%	<0.25%	<0.08%	<0.03%	<0.015%

Typical composition of Ti-6Al-4V – Grade 5 Titanium Alloy

Material	Titanium	Aluminium	Vanadium	Iron	Oxygen	Hydrogen
Grade 5	Bal.	6%	4%	<0.25%	<0.2%	<0.015%

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Steel and Stainless Steel: An iron-based alloy with trace amounts of carbon, chromium, nickel, and molybdenum, stainless steel is a robust and long-lasting metal. The most popular type of stainless steel for orthopedic purposes is 316L, or ASTM F-56. According to ASTM, the L denotes minimal carbon content, and the number "316" designates the material as austenitic.it is used in prosthetic limb components that withstand pressure, such as joints and structural components. its resistance to corrosion, making it suitable for long-term use [14].

Fig 3. a) Stainless steel Component b) Part of Prosthetic made of Stainless steel [14]

Aluminum and its alloy: Its density is roughly one-third that of steel, which is lesser than that of other usual metals. Because of its strong liking for oxygen, aluminum forms a layer of oxide that shields its surface when in contact with air.

Aluminum alloy is well known for its superior corrosion resistance, lightweight, give it a favored material in many fields.

It is used in the manufacture of prosthetic limbs that need stability. It is suitable for structural and supportive components that cannot withstand significant stress [15].

Gold and Silver

In prosthetics, they may not be the most commonly used materials compared to titanium and stainless steel, but they are used in some special applications due to their unique properties. These applications include...

Gold: It is used in some special cases where a material that does not react with the human body and provides an esthetic appearance is required. Used in some special prosthetics that require esthetic precision, such as luxury prosthetics. Gold is also used in the manufacture of some assistive devices containing electrical connections or sensors due to its excellent electrical conductivity.

Silver: Silver is used in some cases, such as prosthetic limbs that require skin contact, but they are not in direct contact with the skin for long periods. They may be used in some precision devices within prosthetics due to their electrical conductivity properties. Silver can also be used as an additive in some manufactured materials to provide additional resistance to bacteria or germs. [16]

History of joint replacement

In 1840, John Murray Carnochan tried to perform the first mandibular arthroplasty by inserting an oak chip, so introducing prosthesis implantation. In 1891, Gluck carried out a total hip arthroplasty (THA) utilizing a femoral head and acetabular cup made from ivory, which was then attached with nickel-plated screws. [17]. The importance of the stiffness and durability of implants in bearing joints became apparent throughout time, causing the use of metallic insertion. Several years later, Robert Jones created a golden cover to resurface a diseased femoral head. Despite the following use of prostheses constructed of rubber, glass [18], and stainless steel [19]. Long-term results showed displeasure with the implants. Attempts to employ materials such as nylon and glass in sick knees also failed. Smith Peterson introduced the first acetabular cup in 1938, made of Cobalt-Chromium-Molybdenum alloy (Co-Cr-Mo), inspired by dental materials [20]. Until the mid-twentieth century, a variety of metals moldings were employed for femoral in knee replacement substitutes, inspired by the usage of Co-Cr-Mo alloy in suffering hips joints. [21]. Today, press-fit or anatomical prostheses have been produced, with some being further modified with hydroxyapatite coating to improve stability or durability [22].

In the last ten years' 3D printing has also been used to manufacture complex components from these alloys, and to improve their mechanical properties through surface treatments [23].

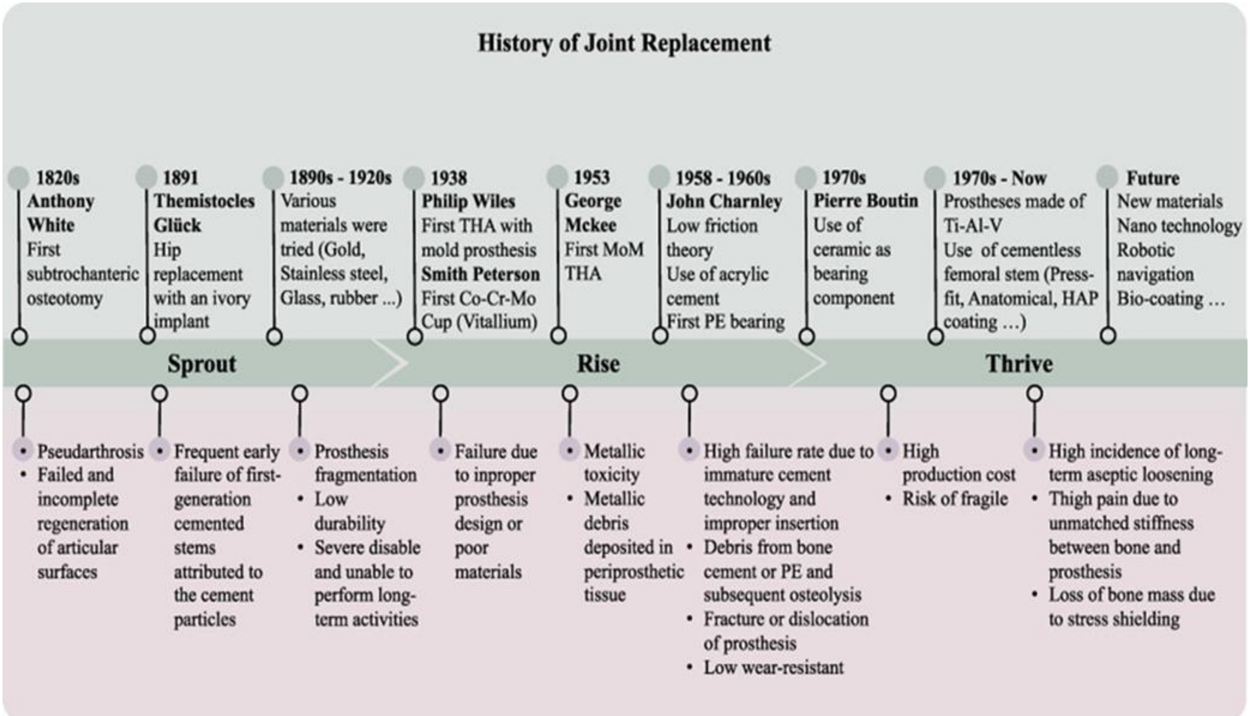

Fig 4 History of joint replacement. [16]

Ijaz et al.; [24] opened a promising path for the design of low-cost aluminum alloys used in the manufacture of lightweight support structures, prosthetic limbs, the study focuses on determining the optimum value of the Ag/Sn ratio, which can be a substitute for the conventional Cu/Mg alloy ratio in Al-Cu-Mg-based alloys without sacrificing key mechanical properties. Result shows the chemical composition and microstructure were found to be the most important variables influencing mechanical properties. The increase in mechanical strength was mainly due to precipitation hardening, with the presence of a micron-scaled Mg_2Sn phase blocking dislocation glide and increasing the alloys' mechanical strength during tensile testing. The alloy with an Ag/Sn ratio of 23 exhibited an average ultimate tensile strength of 450 MPa, nearly four times larger than pure aluminum used in healthcare and medical industries.

Semlitsch, M [25] used pure titanium is preferably for hip cup shells with polyethylene inserts. Result shows that high strength Ti-6AI-4V alloy is mainly used for anchorage stems of femoral components with wear-resistant CoCrMo metal or Al_2O_3 ceramic ball heads. Two new high-strength titanium alloys for implants, developed by Zwicker (Ti-5AI-2.5Fe) and by Semlitsch (Ti-6AI-7Nb) in the last decade, are already in clinical use

Mahdi et al.; [2] studied the tribological properties of titanium alloy Ti-6Al-4V coated with nano-layers of hydroxyapatite (HAp) and silica glass (SiO_2), used in prosthetic limb implants. A results showed that the coated samples had a higher coefficient of friction, this suggests the potential for improving the performance of these alloys in medical applications. The ELECTRE III multiple attribute decision-making method was used to select a light metal for a paediatric prosthetic knee. The study evaluated factors such as patient fatigue, comfort, structural stability, and material cost. Wrought aluminium alloy aluminium 7175 was ranked highest, followed by titanium alloys due to higher costs. Cast aluminium alloys were ranked lowest due to poor structural performance. The study highlights the ongoing improvement of metal alloy properties for prosthetic applications**.**

Clinical studies about metal and metal alloys in prosthetic

Rae, T. [24] The study investigates the toxicity of metals used in total joint prostheses and the risk of tissue necrosis. This has been investigated by incubating primary monolayer cultures of human synovial fibroblasts with various preparations of metals for periods up to 18 day. A result find out morphological changes were observed after exposure to cobalt and nickel chloride, while chromic chloride, ammonium molybdate, and ferric chloride showed no changes. Particulate cobalt and vanadium were most likely toxic due to their high solubility. The only combination likely to give rise to toxic levels of metal under clinical conditions is cobalt-chromium alloy articulating against itself.

Semlitsch, M [25] used pure titanium is preferably for hip cup shells with polyethylene inserts.

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Quintero-Quiroz, C et al .; [16] In this study, a retrospective analysis of 158 cases of bone tumors, primary or metastatic, treated between 2005- 2015 with wide margins resection and tumor implants reconstruction, was performed. The average age was 59 years (range 11-78 years), the same surgeon with antibiotic prophylaxis according to a standard protocol treated all patients. Silver-coated prostheses were implanted in 58.5% of patients and uncoated tumor prostheses in the remaining 41.5%. Patients were re-evaluated annually and complications were recorded, focusing analysis on infective complications. The average follow-up was 39.7 months: 23.4% of patients died at a median time of 35.3 months after surgery; 18.4% developed complications that required new surgery, of which 12.6% of these were due to infection. Patients treated with silver-coated implants developed early infection in 2.2% of cases against the 10.7% of the patients treated with standard tumor prosthesis. The study found that tumor silver-coated implants have a significantly lower early infection rate than traditional implants, with no differences in late infections. Silver blood levels showed no signs of toxicity, and no patients showed signs of local or general toxicity.

Polymer

The most used material for inner part of prosthetic limb and socket. Polymer offer a combination of flexibility, strength, and ease of shaping, Assisting patients with prosthetic limbs with their demands [28].

Types of polymer include…

Polypropylene

Polypropylene: A type of plastic used in a wide range of industrial applications, including the manufacture of prosthetic limbs. It is a polymer-based material with properties that make it suitable for use in certain parts of prosthetic limbs. Polypropylene is characterized by its ability to withstand light loads and many applications that require a strong and flexible material. [29].

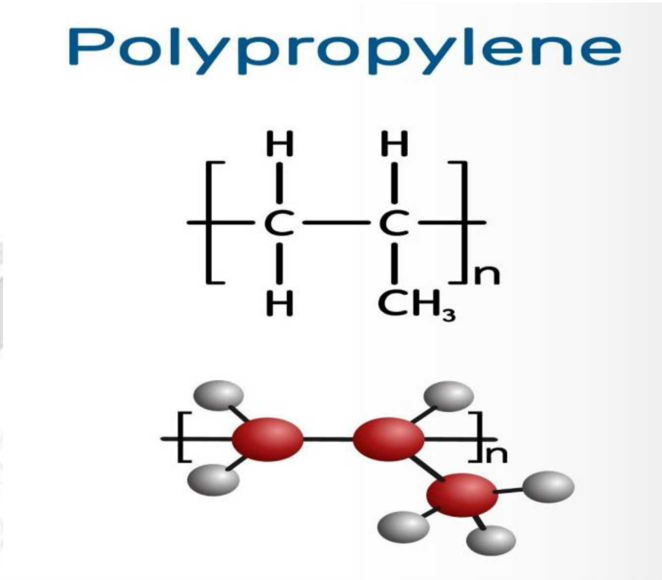

Fig 5. Polypropylene structure

Advantages of Polypropylene in Prosthetics:

1.Light Weight, which helps make the prosthetic limb more comfortable

2.Medium Strength: making it suitable for parts that are not exposed to very heavy loads

3.Good Flexibility: Polypropylene offers a degree of flexibility that allows it to handle to simple movements

4.Good Chemical Resistance: making it suitable for use in a variety of environmental conditions.

5.Corrosion Resistance: It is resistant to corrosion and rust when the prosthetic limb is exposed to moisture [29].

Polyurethane

Isocyanate and alcohol are the two primary constituents of this polymeric substance, which is both flexible and adaptable. Because of its exceptional strength, flexibility, and chemical stability, this polymer may be used in a wide range of fields including the prosthetics sector [30].

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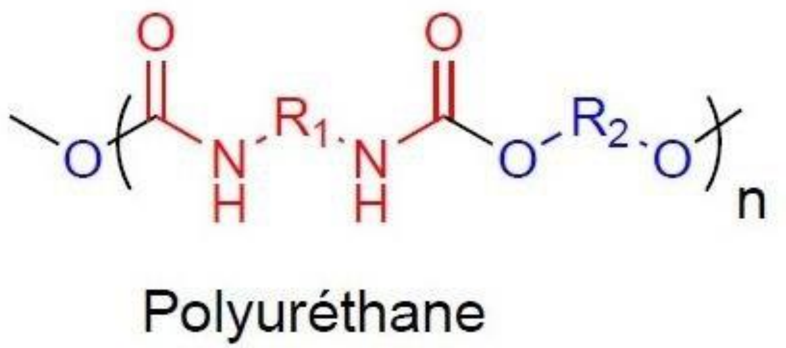

Fig 6. Polyurethane structure

Advantages of Polyurethane in Prosthetics [30]:

1.Flexibility and Comfortable

2.Durability resists abrasion and impact, increase the life of the prosthetic.

3.Ease to fabrication: Prosthetics can be manufactured using this material in a variety of ways

4.Lightweight: Compared to some other materials, like metals

Nylon: This is a trade name for a number of synthetic fibers derived from polymers, primarily composed of chemicals such as adaptic acid and hexamethylene diamine. Nylon is one of the most popular plastics used in various industries due to its multiple properties. [31]

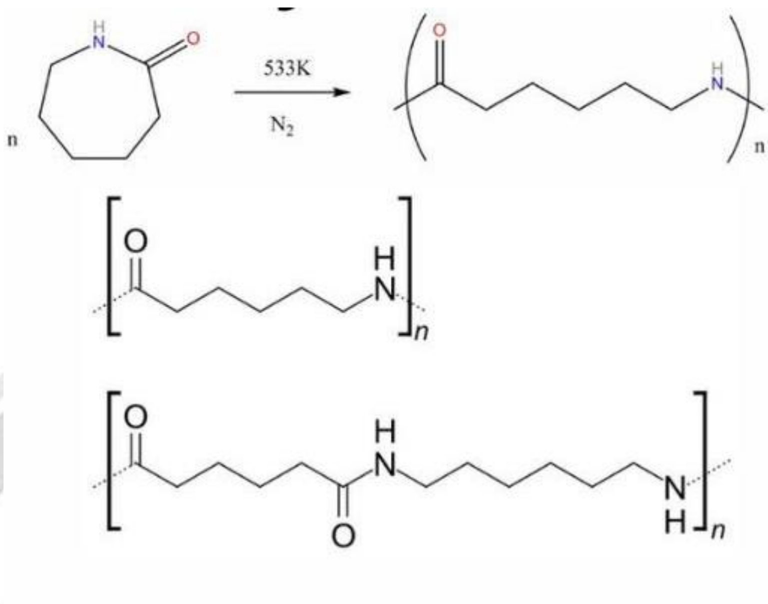

Fig 7. Nylon structure

Advantages of Nylon in Prosthetic Limbs [31]:

1. Strength and durability.
2. Flexibility: Nylon's high flexibility allows for easier movement and comfort all over regular use.
3. Nylon's anti-corrosion properties extends the lifespan of prosthetic limbs by reducing abrasion.
4. Lightweight: Prosthetic limbs made of nylon are lighter and more pleasant for users.
5. Nylon is easily molded into numerous forms, allowing for versatility in prosthesis fabrication.

Silicone: A non-toxic, flexible substance that is a member of the silicone chemical family, silicone is distinguished through its special qualities, including its extreme flexibility and resistance to high temperatures. It is primarily manufactured from silica, a natural material that can be modified to suit various industrial applications [32].

Advantages of Silicone in Prosthetics:

Silicone is a versatile material that offers several advantages in prosthetics, including high comfort, non-toxicity, water resistance, durability, and adaptability to body temperature. Its flexibility allows it to adapt to user movements, reduce friction, and maintain good performance even in humid environments. Its adaptability also helps reduce stress caused by temperature changes [32].

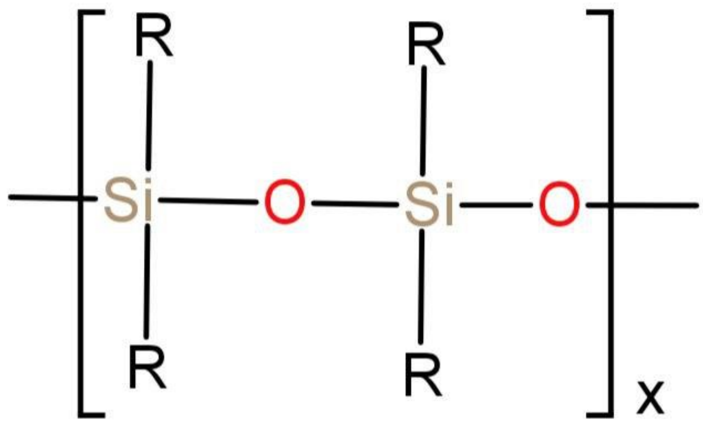

Fig8. Silicone structure

Uses of Silicone in Prosthetics:

1. Liners and Covers: Prosthetic limb linings and coverings are made of silicone.
2. Customizable Prosthetics: Because silicone can replicate the natural shape, it is sometimes used to create whole prosthetic limbs or specific parts, like fingertips or toes.
3. Pneumatic and Hydraulic Systems: Because silicone is malleable and insulating, it is utilized in certain prosthetic limbs that have pneumatic or hydraulic systems.
4. Fixed and Removable Prosthetics: Because silicone is flexible and allows for comfortable movement, it can be utilized in certain fixed or changeable prosthetic limbs. [32]

Jweeg, M. J., [33] did experimental study to compare the stiffness of five prosthetic sockets made of different materials. Compression, three point flexural and tensile tests are implemented by the Testometric machine. The laminate sockets give better results in compression than polypropylene. Polypropylene gives good results in bending compared with the laminate sockets. When the socket loads are mainly in compression i.e. the low activity level patients, it seems that any of the tested sockets could be used, however, when the load will be not only in compression but in flexion as well i.e. high activity patients, socket No.1 and 5 could be used.

Etcheverry, M., etal .;[34] investigated a new route for improving GF/PP adhesion using in-situ polymerization of PP onto fibers, resulting in increased strength, toughness, and interfacial strength in PP/GF composites, as confirmed by fragmentation tests and mechanical properties measurements.

Muzio, G et al.;[35] studied the coated polypropylene prostheses with a silver nanoclusters-silica composite (Ag/SiO2) layer to prevent abdominal infections after hernia repair. The coating was placed to either two polypropylene layers or the mesh layer alone. The coating was designed to maintain antibacterial activity with biocompatibility. Initial investigations revealed that coating both layers resulted in antibacterial characteristics but reduced prosthetic biocompatibility. The Ag/SiO2-coated mesh layers facilitated fibroblast growth and activity without causing cell death. and providing antibacterial activity.

Kuret, Z. etal.; [36] involved 42 patients with single or multiple finger amputations evaluated their adjustment to amputation and prosthesis use using the Trinity Amputation and Prosthesis Experience Scales (TAPES). Results showed that most patients had a single finger amputated, with average scores above 50% of the maximum possible score. Silicone prostheses play a crucial role in amputation adaptation, offering aesthetically satisfying results and alleviating social interactions, thereby improving the amputee's quality of life.

Kadhim, F. M et al.; [37] Improved mechanical properties of polypropylene by adding reinforcing materials (such as short glass or carbon fibers) or modifying the molecular structure to increase toughness and fatigue resistance. Comparison of three types of composite materials as an alternative to polypropylene in the manufacture of prosthetic bases. Results shows increase in yield stress, ultimate stress, and modulus of elasticity by up to 72%. The best proposed material is from Group III (layers of bamboo and carbon fiber).

Atkinson, J. R et al; [38] made a physical and mechanical tests have been conducted and scanning electron microscopy carried out in order to characterize a high density polyethylene cross-linked using vinyl trimethoxysilane. It is suggested that this cross-linked polyethylene could be an alternative to high molecular weight polyethylene for prosthetic applications.

Williams, J. O et al.; [40] presented a alternate strategy to create these sensors: Ethylene had been polymerized with nickel as the catalyst to produce a polymer with up to 93 branches for 1000 of carbon atoms. This branching polyethylene was flexible and had larger volumes than high-density polyethylene. Polyethylene specimens demonstrated superior thermal coefficient of resistance and resistivity to electricity after being heat pressed with a graphite infill to make a conductive, flexible sensor. The technology is repeatable and offers a path to uniform, cost-effective sensors for potential prosthetics technologies.

2. Polymer Composite Material

The past few years have been significant advances in the production of current artificial limbs. Composites are designed materials comprised of two or more elements, each with unique physical qualities that can be combined synergistically [41]. Composite materials are classed based on their composition, which comprises both basis and filler components. The base material that binds or holds the filler substance in patterns is known as a matrix, whereas the filler material might take the shape of sheets, pieces, particles, fibers made of natural or synthetic materials. As shown in (Figure 9), composites are divided into three major types based on their structure.

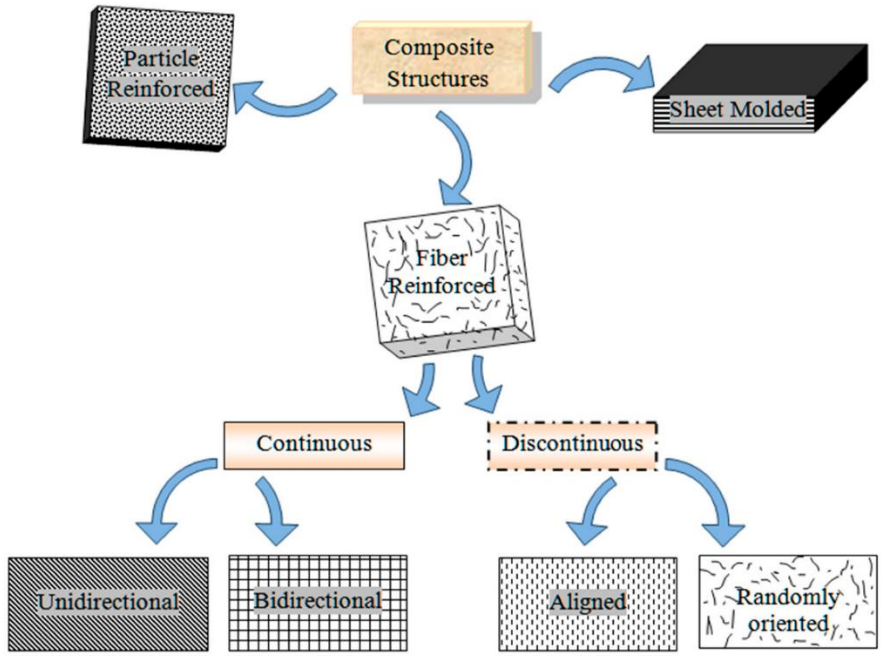

Fig 9. Classification of Composite [41].

The most popular multiphase materials in orthopaedics right now are fiber-reinforced polymer composites. Additionally, a lot of prosthetics for the upper and lower limbs created today are composites with an underlying polymer matrix. These materials are advantageous because of their outstanding strength to weight ratios and excellent biocompatibility. as well as their superior biocompatibility [42], [43].

Fiber Reinforced Composites

Composites made of fiber-reinforced polymers can efficiently achieve both high strength and low elastic modulus. Additionally, the use of composite materials significantly enhances resistance to fatigue and corrosion resistance [44]. There are several ways to modify these materials' features. For example, altering the volume fraction or the configuration of the reinforcing fibers can dramatically alter the properties of the material. Thus, fiber reinforced polymer composites, in particular, have the capability to be extremely biocompatible. Synthetic fibers are manufactured by humans through chemical reactions and are further divided into both organic and inorganic categories according to their composition. Fiber materials constitute a load-bearing component of the composite construction because their strength and stiffness are often far greater than those of the matrix material [45].

1. Natural Fiber-Reinforced Composites

The utilization of natural fibers as reinforcement materials in composite materials has garnered significant attention owing to their distinctive properties. Derived from diverse sources (Figure 10), such as plants, animals, and minerals, natural fibers have become increasingly popular in recent years owing to their cost-effectiveness, biodegradability, and renewability. Natural fibers, such as jute, flax, and hemp, have a strong-to-weight ratio, making them ideal for composite materials like lower-limb prosthetics. Their low density contributes to weight reduction, making them an eco-friendly alternative to synthetic fibers. However, moisture absorption is a concern, and techniques like alkali treatment and hydrophobic additives can mitigate this. Despite these challenges, natural fibers offer a sustainable solution for composite materials, reducing environmental impact and promoting sustainability in the design of lower-limb prosthetics. Natural fiber-reinforced composites (NFRCs) are materials made from natural fibers embedded within a polymer matrix. The choice of the matrix significantly impacts the composite's mechanical properties and performance. Common materials include polypropylene, polyester, and epoxy. Bio-based epoxy resins from renewable sources can improve NFRCs' biodegradability and environmental impact [46]. However, challenges like fiber-matrix compatibility and moisture sensitivity still hinder their use in heavy-duty applications like prosthetic devices. NFRCs' tensile strength, flexural strength, impact resistance, and fatigue behavior are crucial factors to consider.

NFRC's Flexural Strength and Impact Resistance in Prosthetics

- NFRCs have a high flexural strength, making them appropriate for load-bearing applications.
- Flexural qualities are influenced by fiber content, length, orientation, and matrix parameters.
- Proper fiber-matrix interactions and proper dispersion are essential for increased flexural strength.
- Impact resistance of NFRCs is critical in prosthetic design, since it determines energy absorption and dissipation during dynamic loading.
- Other factors that influence impact properties include fiber selection, chemical treatment, and matrix qualities.
- Comprehensive examinations and optimization of impact resistance are critical for lower-limb prosthesis' durability and functionality.[]

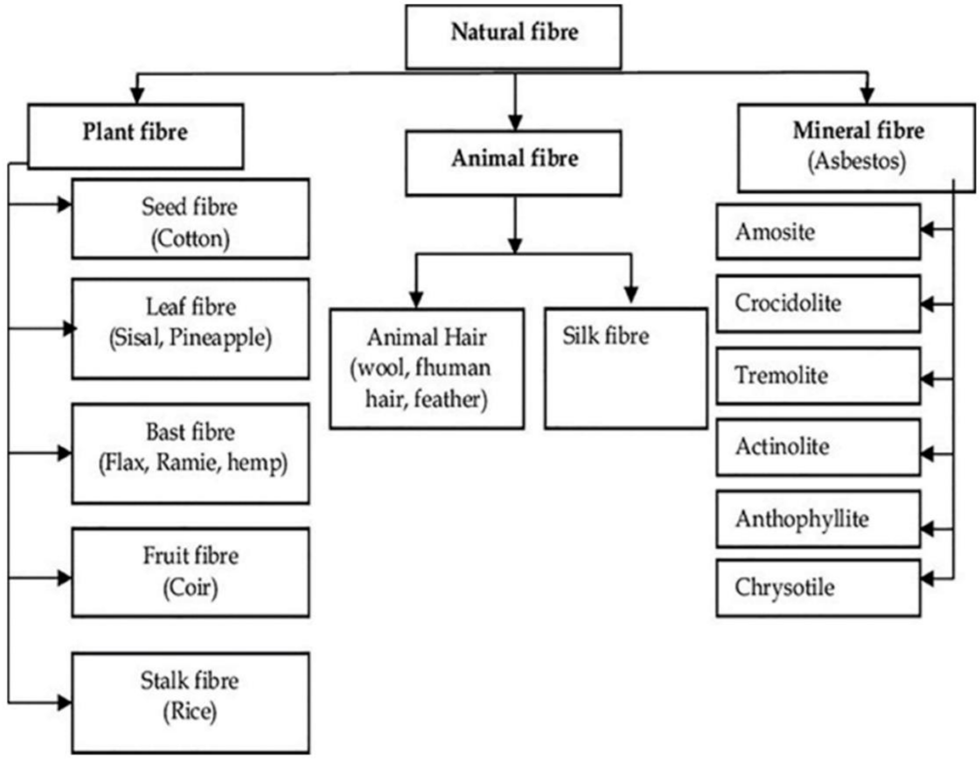

Fig 10. Glass fiber Classification of natural fibers based on their origin: plant, animal, or miner [46]

A study by Irawan et al. [47], the manufacturing of lower-limb prosthetic sockets using ramie fibers and epoxy composites was suggested. Their results showed that such sockets had a significant impact on comfort because of their light weight, strength, and flexibility compared to fiberglass sockets. Furthermore, sockets fabricated with the ramie fibers exhibited a considerably lower weight than those made with fiberglass, with a difference of 186 g, representing a 46.26% reduction.

Moreover, a study by Mankai et al. [48] showed that esparto fibers (Stipa tenacissima) are a promising alternative material for manufacturing prosthetic sockets. Their fatigue testing results revealed the viscoelastic behavior of the material and estimated its lifespan to be 2,325,000 cycles, satisfying 77.5% of the ISO 10328 objective.

These studies provide evidence for the potential of NFRCs in lower-limb prosthetic designs. The utilization of these composites can result in lightweight, strong, and biocompatible prostheses

2. Synthetic Fiber-Reinforced Composites

Composite materials, including fiber reinforced polymer composites, have significantly improved orthopaedics and prosthetic device design due to their superior strength, weight, and biocompatibility. The most fiber used in prosthetic are carbon and glass fiber

Glass fiber

Glass fiber is one of the strongest known fibers, and it is largely employed as the primary reinforcing material in polymer composites for a variety of purposes. However, because to its expensive price, many natural fibers were added to make the composite more affordable. Furthermore, glass fiber is exceedingly brittle, thus it is generally reinforced with ductile natural fiber to lessen the brittleness of hybrid polymer composites [49].

Carbon fiber

The use of carbon fiber reinforced polymer (CFRP) composites in the structural design of prosthetic limbs transformed the capacity of amputees to compete in sports. Lower limb prosthesis can incorporate an energy return system because to CFRP's exceptional strength and flexibility, which makes it a very lightweight material [49]. Considering improvements in biomechanics and gait analysis, the requirement for such a system was acknowledged, and it was initially implemented in the Seattle foot in 1981. Energy is kept when body weight is transferred to the CFRP structure, which creates compressive loads. Decompression occurs when the body weight is removed, allowing the material to regain its previous shape and, as a result, energy. When developing any energy store and return (ESAR) foot, it is crucial to take into account the system's natural frequency because the amputee/prosthetic system's dynamic response is dependent on the patient's height, weight, and degree of activity [50].

Khare et al. [50] investigated the impact of various resins on the physicomechanical characteristics of hybrid fiber-reinforced polymer composites that are applied in human prosthesis .Result showed the influence of different resin on physico-mechanical properties of hybrid fiber reinforced polymer composites were observed. Composites for prosthetic limb were manufactured with constant 5 wt% glass fiberhybridised with varied jute and grewiaoptiva loading (2.5 wt%, 5 wt% and 7.5 wt% each) reinforced based epoxy, vinyl ester and polyester matrix.Results show that the strength and hardness get improved as the ratio of natural fiber increases.The highest tensile, flexural,were obtained forepoxy-basedhybrid composite at 7.5 wt%, vinylester based hybrid composite at 5 wt% samples E3, V2, E3 and E2 respectively. In addition, both Impact energy and hardness were observed to be maximum for epoxy based hybrid composites at 7.5 wt% and 5 wt% respectively. Results also reveal that 5 wt% glass fiber (fixed), 10 wt% natural fibre with epoxy is the best composition among fabricated samples followed by the vinyl ester composite ofthe same composition. As evidence, TOPSIS results also convey the best composition among the fabricated composites.

Bombek M . et al.; [51] compared existing material (A) with three new materials that changed the lamination process: B1, B2, and B3. The specimens underwent laboratory strength testing, and the results showed no significant differences in bending strength, tensile strength, or compressive strength between the materials. Material A had the highest bending strength, but no significant differences after adjusting for specimen thickness. The researchers plan to continue research and development in laminated composite prosthetics with a more systematic, technological approach

Material A(the standard material used as a control group in the study)

Vol. 33, No.4. \ 2025 ISSN: 2616 - 9916

Material B1,2,3(This material involves a modified lamination procedure using an infusion spiral tube for resin application)

Tallal et al .;[52]The study aimed to provide a high-performance, easy-to-use, and affordable sports prosthetic foot for amputees who have lost their lower limbs. Six laminates of composite material, consisting of matrix orthocryl lamination 80:20 pro reinforced with different fibers (Kevlar fibers, carbon fibers, glass fibers, and perlon fibers), were fabricated and cut to the required dimensions. The mechanical properties of the laminates were calculated using the rule of mixtures and ANSYS program. Carbon fiber-reinforced laminates were found to be better in Young's Modulus and deformation.

Kadhim etal.;[53]studied compares new composite materials—layers of bamboo, fiberglass, Perlon, and carbon fiber—as alternatives to polypropylene for prosthetic sockets. Mechanical tests showed that the bamboo-carbon fiber composite had significantly improved strength and elasticity. Interface pressure measurements and finite element analysis confirmed its ability to withstand loads safely. The results indicate that the third composite group is the best option due to its high mechanical performance. Overall, the study suggests these composites can enhance socket durability and comfort.

Paz-González et al.;[54] made 3D printed polylactic acid/carbon fiber laminates (PLA/CFRC) composite that can substitute material for femoral stem prostheses. improved the mechanical properties of 3D-printed prosthetic leg sockets by using post-processing techniques. Fifteen sockets were reinforced with carbon fiber, carbon-Kevlar fiber, fiberglass, and cement.

Kumar et al.; [55] investigated natural polymers with fiber reinforcement in knee prosthesis for their better flexibility and reduced weight, which give superior specific strength and stiffness than traditional biomaterials.

Widayat, W etal .:[56] determine the bending and impact strength of the laminatecomposite Co/G/Co (cotton - glass fiber - cotton) and C/G/C (carbon fiber - glass fiber - carbonfiber) that are used by Garuda Medica, an orthotic and prosthetic manufacturer in Tridadi,Sleman Regency, to make prosthetic sockets. Co/G/Co and C/G/C laminate composites withlayer variants of 2/1/2 and 4/2/4 for each composite were made by hand layup method. Allvariants were tested for their flexural and impact strength. The addition of the laminate layerand the replacement of the outer laminate increase the strength of the composite. Thereplacement of the outer laminate from cotton to carbon increased the strength. The lowestimpact strength of the composites, namely the [Co2/G/Co2] variant, has met the requirement ofthe socket impact strength that is suitable for use. However, the stacking sequence of Co/G/Coand C/G/C are not recommended when viewed from the strength and classification of theconstituent laminate

- **Comparison between the material**

Based on the all above we can make table contain the material for all part of prosthetics and property of each material and alternative of material to design same part with the same feature

Table 4.1 Comparison between material and their functional performance

Material	Properties	Functional performance	Alternative
Metal			
Titanium	It is considered one of the strongest and lightest	High performance	Carbon fiber
Stainless steel	Strong and durable metal, corrosion-resistant	Moderate performance(heavy weight)	Titanium
Aluminum	Has less strength than steel and titanium. Light weight with good abrasion resistance.	Good performance	Titanium
Polymers			
Polypropylene(PP)	Light weight and flexible material/medium strength /easy to form and cast	Moderate performance	Polyethylene
Polyethylene	Resistant to slipping / High resistance to heavy impacts/Does not offer advanced performance	Good performance	Polypropylene
Polyurethane	Good flexibility, load-bearing capacity, light weight.	Excellent functional performance for socket liner	Silicone
Nylon	Strength, durability, flexibility, lightweight	High functional performance for parts requiring high strength	Polyethylene
Silicone	Flexibility, safe and non-toxic / waterproof, good durability	High functional performance and a suitable choice for parts that require high flexibility and high biocompatibility	Polyurethane
Reinforced Fiber			
Carbon Fiber	Light Weight, Very Strong, Flexible, Corrosion Resistant	High performance	Glass fiber
Glass fiber	Light Weight, Very Strong	High performance	Carbon fiber

Vol. 33, No.4. \ 2025 ISSN: 2616 - 9916

Studies that include the characteristics and comparisons between the materials used to manufacture prosthetic limbs, with the best material being selected based on specific characteristics

One of studies by Aherwar [57] compare between stainless steel and cobalt alloy with titanium and found out that titanium is best material for prosthetic than other alloys

Aherwar, A., [57] Compared to more traditional stainless steels and cobalt-based alloys, Increased use of titanium alloys as biomaterials is occurring due to their lower modulus, superior biocompatibility and enhanced corrosion resistance when compared to more conventional stainless steels and cobalt-based alloys. These attractive properties were a driving force for the early introduction of α (cpTi) and α+β (Ti–6Al–4V) alloys as well as for the more recent development of new Ti-alloy compositions and orthopaedic metastable β titanium alloys. The later possess enhanced biocompatibility, reduced elastic modulus, and superior strain-controlled and notch fatigue resistance.

Results shows that the poor shear strength and wear resistance of titanium alloys have nevertheless limited their biomedical use. Although the wear resistance of β-Ti alloys has shown some improvement when compared to α+β alloys, the ultimate utility of orthopaedic titanium alloys as wear components will require a more complete fundamental understanding of the wear mechanisms involved. This review examines current information on the physical and mechanical characteristics of titanium alloys used in artifical joint replacement prostheses, with a special focus on those issues associated with the long-term prosthetic requirements, e.g., fatigue and wear**.**

Kaufman KR et al.; [58] A study comparied the biomechanical performance and prosthesis-related quality of life of 10 experienced male subjects with unilateral transtibial amputations found that using a fiberglass prosthetic foot design compared to traditional carbon fiber ESR designs resulted in increased ankle dorsiflexion, similar ankle moments, and increased ankle power generation. The fiberglass foot also had greater energy absorption during gait, with no difference in energy return. The subjects expressed improved prosthesis-related quality of life with the fiberglass foot. The findings suggest that the new ESR foot design offers better performance.

Results: Gait data demonstrated increased ankle dorsiflexion ($P < .01$), similar ankle moments ($P = .07$), and increased ankle power generation ($P = .01$) when using the fiberglass foot. The fiberglass foot had greater energy absorption during gait ($P = .01$) with no difference in energy return ($P = .37$). The subjects expressed improved prosthesis-related quality of life with the fiberglass foot ($P = .01$).

Conclusions: The findings of this study demonstrate that the new ESR foot comprising a fiberglass material had better performance than traditional designs using a carbon fiber material.

- Abased on study of Kaufman [58] the study compares between the carbon fiber and glass fiber the result found out that glass fiber ankle offers better performance than carbon fiber.
- Another study Kumar [54] highlights on natural polymers with fiber reinforcement in knee prosthesis for their better flexibility and reduced weight, which give superior specific strength and stiffness than traditional biomaterials .

- Another study by Raihan [59] showed that the best material for pylon is polymer/carbon fiber composite

Raihan Kenji.; [59] selected the best pylon material, part of below-knee leg prosthetic, has been performed. It begins with function analysis to generate design requirement, which concludes that the objective is to select material that gives proper mechanical properties with lowest weigth and cost. Constraint requirements eliminate unsuitable material. Material indices, ascoring function, are derived from objective with respect to a function, and used for ranking material candidates. Ranking from material indices gives top material candidates of woods. Al alloy, Mg alloy, and ferrous alloy. Further seek of documentation is undertaken by failure analysis, value analysis, fabrication, and environmental impact. The final decision is PLA carbon fibre is the best material for pylon of below knee in respect to performance to weight and cost.

- However, abdalikhwa study showed comparison between polymer(PMMA) reinforced by two kind of fiber (glass fiber and carbon fiber)

Abdalikhwa [60] showed the hung innovations and developments of new suggested composite material, to modify the prosthetic pylon (which is generally made of lightweight metal such as aluminum, titanium, stainless steel, or an alloy of these), extends its life and increase the comfort of its user. Vacuum bagging technique was used to manufacture the samples which consist of constant perlon layers and a different number of composite material (Carbon or Glass) fiber layers as reinforcement materials at (0°/90°) orientation relative to the applied load and polymethyl methacrylate (PMMA) as a resin. The work included two major parts; theoretical and experimental tests for the real case. The theoretical and experimental Results showed that the modulus of elasticity, tensile strength, and critical buckling load increase with the increasing the number of composite fiber layers. The percentage of increase in modulus of elasticity, tensile strength and critical buckling load for the specimen with three carbon layers and perlon layers in PMMA matrix was compared with three glass layers and perlon layers in PMMA matrix specimen and it was (12.5%, 5% & 17%) respectively, at (0°/90°) fibers orientation relative to the applied force. Validation of the results is conducted by comparing with results in other literature, a good agreement between them was found

Oleiwi, J. K [61] Compared to traditional prosthetic pylon materials (Aluminum, Titanium, or Stainlesssteel.), composite prosthetic pylon materials are used instead of metals. Vacuum bagging technique was adopted for the preparation of specimens made of Poly methyl methacrylate (PMMA) as matrix with constant Perlon layers and different number of Hybrid (Carbon + Glass) fibers layers as reinforcement materials at (±45º&0º/90º) orientation relative to applied load. Also the finite element method (ANSYS-15) were used by create a model of prosthetic pylon and applied compressive load at heel strike step from gait cycle to known the critical buckling stress. The experimental and numerical results shown that the tensile strength, modulus of elasticity, and critical buckling stress increases with increasing number of Hybrid fibers layers, that equal to (145 MPa, 6.25 GPa, and 670 MPa) respectively, and the percentage of increase in tensile strength, modulus of elasticity, and critical buckling stress for specimen with three Hybrid (Carbon + Glass) layers and Perlon layers in PMMA resin compared with pure PMMA specimen was (302.7% , 300% & 257.22%) respectively, at (0º/90º) fibers orientation relative to tensile force.

Estillore, J. [62] Discuss the selection for the fabrication of transtibial prosthesis in developing countries is favoring what materials can be readily available. Given numerous options, a multi-criteria decision-making process can be effectively implemented to choose the optimal materials based on design requirement without compromising the target mechanical properties and comfort for the patient. In this study, analytic hierarchy process (AHP), technique for order preference by similarity to ideal solution (TOPSIS) and preference ranking organization method for enrichment evaluations (PROMETHEE) methods were used as a decision-making tool for materials selection of prosthetic socket and pylon tube. The criteria for the candidate materials such as flexural strength, tensile strength, modulus of elasticity, yield strength and impact strength were evaluated and each criterion was given a weight using AHP, while the materials selection calculation was done using TOPSIS and PROMETHEE. For the prosthetic socket, same ranking was observed for both TOPSIS and PROMETHEE. The carbon fiber reinforced composite (CFRC) was ranked first and closely followed by pineapple fiber reinforced composite (PFRC). TOPSIS ranked PFRC highest for the pylon tube material, followed by titanium alloy while this ranking was interchanged in PROMETHEE, putting first preference for the use of pineapple fiber reinforced composite then followed by titanium alloy. Therefore, the pineapple fiber reinforced composite can be an ideal alternative for the standard carbon fiber socket and titanium pylon tubes in fabricating a transtibial prosthesis.

Summary:

- Prosthetic limbs and supports are made from a variety of materials, selected based on factors such as weight, durability, cost, and user comfort.
- Titanium, Aluminum and Stainless Steel: Provide durability while maintaining a low weight. These metals are widely used in structural components of prosthetic limbs.
- Polypropylene: Used in many industrial applications, including prosthetics, it is known for its ability to withstand light loads.
- Polyurethane: A flexible and adaptable plastic material, characterized by its flexibility and strength.
- Silicone: its ability to withstand high temperatures and high flexibility make suitable for inner part.
- Composite materials consist of two or more components, such as fiber-reinforced polymer composites, which are currently used in prostheses. These materials are characterized by

their strength, light weight, and biocompatibility. Its properties can be modified by changing the fiber composition.

- Composite materials represent a new era in the development and manufacture of limbs, as they possess properties that combine the properties of their components. Research has proven that they are the strongest, most flexible and most durable materials.
- Carbon fiber:

  Advantages: Lightweight, very strong, flexible, corrosion resistant

  Disadvantages: Expensive, difficult to manufacture and repair

  Common uses: High-performance upper and lower extremities, sports supports
- Glass fiber has many properties that make it suitable for use in various engineering applications, including prosthetics.
- Thru comparing the materials used in research and studies, it was found that titanium alloys are the most commonly used and the most efficient in the production of prosthetics. When comparing the performance of ankle made from carbon fibers and glass fibers, the ankle and feet made from carbon fibers are more efficient and perform better.
- Composite and fiber-reinforced materials are the future direction in prosthetic manufacturing and are superior in this field compared to traditional materials.

Future direction

The emphasis will be on smart and adaptive materials, such as self-healing polymers and biologically renewing materials, to improve lifespan and get rid of the need for frequent replacements. The future research will also look into combining nanoparticles to increase mechanical qualities and produce biocompatible surfaces that minimize rejection.

The other method is to create materials that enable the direct integration of biotechnology and electronics into the limb, resulting in more natural sensory and motor responses.

Finally, in the near future, lightweight, high-strength materials will be developed to mirror the qualities of human bones and tissues, thereby improving user comfort and prosthetic efficiency.

Acronyms list

THA total hip arthroplasty

TAPES Amputation and Prosthesis Experience Scales

NFRCs Natural Fiber-Reinforced Composites

CFRP carbon fibre reinforced polymer

SACH Silent Ankle Cushion Heel

PLA Polylactic acid

CFRC carbon fiber laminates

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من المعادن للمواد المركبة :مراجعه شامله للمواد المصنعه للطرف الصناعي

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الخلاصة

شهد مجال الأطراف الصناعية تطورًا كبيرًا وشاملًا مع التقدم في استخدام المواد للأطراف الصناعية. في الماضي، كانت الأطراف الصناعية تُصنع من الخشب، لكن الصناعة تطورت لتشمل المعادن وسبائكها. ومع ذلك، فإن قيود هذه المواد دفعت الباحثين في مجال علوم المواد إلى البحث عن بدائل أكثر تقدمًا ومرونة. مؤخراً، كان هناك تحول نحو استخدام المواد البوليمرية، والمواد المركبة، والألياف مثل ألياف الكربون والزجاج بسبب خصائصها المرغوبة، مثل خفة الوزن، وقوة الألياف، وسهولة التشكيل، ومرونة البوليمرات، مما جعل الحياة أسهل لمستخدمي الأطراف الصناعية. تستعرض هذه المراجعة التطورات في تصنيع الأطراف الصناعية من حيث المواد المستخدمة وملاءمتها لكل جزءٍ من الأطراف الصناعية السفلية.

الكلمات الدالة: –صنيع الطرف الصناعي، المعادن، بوليمر، المواد المركبه، الياف الكاربون، الياف الزجاج.