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EXPLORING MATERIALS AND TECHNIQUES IN JAIPUR FOOT MANUFACTURING: A REVIEW

Anisha Nitin Mijar
Department of Mechanical Engineering,
Vishwakarma Institute of Information Technology, Kondhwa bk, Pune, India

ABSTRACT

The Jaipur Foot is a remarkable prosthetic limb that plays a pivotal role in restoring mobility and independence to individuals with lower limb amputations, especially in resource-constrained settings. This paper embarks on a comprehensive exploration of the materials employed in the construction of the Jaipur Foot, delving into their mechanical properties. By synthesising a range of scientific articles, including studies utilising finite element analysis, clinical evaluations, and material-specific investigations, this review endeavours to offer profound insights into the meticulous selection and optimization of materials for the Jaipur Foot. The primary objective of this review is to make substantial contributions to the ongoing development of highly efficient and cost-effective prosthetic devices, thus uplifting the lives of individuals in need.

Keywords: Jaipur Foot, Prosthesis, Amputation, Mechanical Properties, Material Optimization, Biocompatible Materials.

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INTRODUCTION

The Jaipur Foot, developed in the 1970s in Jaipur, India, revolutionised the field of prosthetics by offering a low-cost and functional solution for individuals with lower limb amputations. This artificial limb incorporates a unique design that utilises lightweight materials to enhance mobility and comfort for the users. However, the selection of appropriate materials for the Jaipur Foot is crucial to ensure durability, biomechanical compatibility, and cost-effectiveness. This review aims to summarise and analyse the research conducted on the materials used in the Jaipur Foot to provide a comprehensive understanding of their properties and performance. [6]

METHODS

To ensure a comprehensive review, a systematic search was conducted across multiple databases, including PubMed, Google Scholar, and scientific journal websites. The keywords "Jaipur Foot" and "materials" were used in combination to identify relevant studies. The search encompassed articles related to various analyses, including finite element analysis studies, clinical evaluations, and material-specific investigations. By employing this rigorous approach, a diverse range of literature was examined, enabling a thorough exploration of the materials used in the Jaipur Foot and their associated research findings. This research was also aided by a visit to BMVSS Jaipur, Rajasthan.

MANUFACTURING PROCESS OF JAIPUR FOOT

1) **Negative Cast Creation**: The manufacturing process of the Jaipur foot begins with the creation of a negative cast of the residual limb. This involves taking an impression of the limb, typically using plaster or another suitable material. During this step, the areas that bear the most weight, such as the heel and the ball of the foot, are carefully identified and marked to ensure proper alignment and support in the final prosthesis. The load bearing areas are then indented while the cast is still mouldable. Later the cast is filled with plaster of Paris cement.

Figure 1 A Negative Cast made of Plaster of Paris

2) **Positive Cast Formation**: Following the negative cast, a positive cast is made using a combination of soft-liner HDPE (High-Density Polyethylene) pipe(elastomer) and EVA (Ethylene Vinyl Acetate) sheet (elastomer). These materials are chosen for their flexibility, durability, and ability to conform to the shape of the residual limb. The positive cast serves as the foundation upon which the rest of the prosthesis will be built. An additional benefit of these being that they are considerably light weighted and sturdy. The negative cast is inserted in the HDPE pipe along with the EVA sheet wrapped around.

Figure 2 A positive cast.

3) **Covering with HPEV Material**: Once the positive cast is prepared, it is covered with HPEV (High-Performance Ethylene Vinyl Acetate) material (elastomer). This serves as an additional layer of protection and reinforcement, enhancing the structural integrity of the prosthesis. HPEV is known for its lightweight nature and excellent shock absorption properties, making it an ideal choice for prosthetic devices.

4) **Heating and shaping of HDPE Pipe**: The HDPE pipe, which forms the structural core of the prosthesis, is then heated to a temperature of 250°C. This high heat allows the pipe to become pliable, enabling it to be shaped and moulded according to the specific requirements of the individual's residual limb. Careful attention is paid to achieving the correct alignment and fit to ensure optimal comfort and functionality.

Figure 3 The cast is mounted in the oven with a stocking on.

5) **Utilization of Stocking**: To prevent the HDPE pipe from melting or deforming during the heating process, a stocking is used to shield the material. This protective layer helps maintain the integrity of the pipe while allowing it to be heated to the necessary temperature for shaping. By carefully controlling the heating process, the manufacturing team can achieve precise adjustments to the prosthesis as needed.

6) **Layering Sequence**: The layering sequence during the construction of the Jaipur foot involves placing the stocking, EVA sheet, and heated HDPE pipe in a specific order. This meticulous arrangement ensures that each component contributes to the overall structure and function of the prosthesis, providing stability, support, and comfort to the user.

7) **Attachment of Lower Part with Screws**: Once the shaping and layering process is complete, the lower part of the prosthesis, representing the foot, is securely attached to the rest of the device using screws. This step ensures that the components are firmly connected and aligned, minimizing the risk of dislodgement or malfunction during use.

8) **Application of Etha Flex Sheet**: To further enhance comfort and usability, an Etha Flex sheet (elastomer) is attached along the edges of the prosthesis. This soft lining material serves as a cushion between the device and the user's skin, reducing friction, pressure points, and discomfort. Etha Flex is chosen for its hypoallergenic properties and ability to provide a gentle yet supportive interface.

9) **Incorporation of Iron Alloys in Above-Knee Prostheses**: In addition to the aforementioned steps, above-knee prostheses may incorporate iron alloy components. These components are strategically placed within the prosthesis to provide additional weight and stability, mimicking the natural biomechanics of a human leg and improving the user's gait and balance. Iron alloys are valued for their density and durability, making it a suitable choice for enhancing the functionality of prosthetic limbs.

Figure 4 Above knee Jaipur foot with Stanford knee joint.

RESULTS AND DISCUSSION

The comprehensive review of literature unveiled the materials utilised in the construction of the Jaipur Foot, encompassing polyethylene (high-density and ultra-high-molecular-weight), polypropylene, aluminium, wood, and rubber. Each of these materials possesses distinct properties that play a crucial role in determining the overall functionality and performance of the prosthetic limb. The Jaipur Foot has reached its pinnacle as a prosthetic solution primarily due to its cost-effectiveness, making it accessible to a wide range of individuals, especially in resource-constrained settings. By utilising affordable materials and innovative design principles, the Jaipur Foot has provided mobility and independence to countless lower limb amputees worldwide. However, while the Jaipur Foot has achieved remarkable success, potential advancements in the field continue to be explored. Further advancements may include the integration of advanced materials for enhanced durability and performance, as well as the development of more personalized and customizable prosthetic solutions tailored to individual user needs. These potential advancements are discussed in more detail in subsequent sections of this paper, aiming to propel the Jaipur Foot towards even greater heights in the field of prosthetics.

MATERIALS USED AND THEIR PROCESSING TECHNIQUES

Polyethylene (HDPE and UHMWPE)

Polyethylene, specifically high-density polyethylene (HDPE) and ultra-high-molecular-weight polyethylene (UHMWPE), plays a crucial role in the construction of the shank (part that connected ankle to the foot) or socket of the Jaipur Foot due to their distinct properties.

HDPE, renowned for its exceptional strength, wear resistance, and dimensional stability, is commonly used in load-bearing components of the Jaipur Foot. These properties enable HDPE to withstand the forces exerted during daily activities, ensuring the longevity and durability of the prosthetic limb. Moreover, HDPE's dimensional stability contributes to maintaining the structural integrity of the Jaipur Foot over time.

On the other hand, **UHMWPE** offers a unique set of characteristics that enhance the functionality of the Jaipur Foot. With its superior impact strength, UHMWPE provides enhanced resistance to sudden shocks and forces, allowing the prosthetic limb to withstand demanding activities. Additionally, UHMWPE exhibits low friction properties, reducing the resistance between moving parts and facilitating smoother movement for the user. This low friction characteristic is particularly beneficial in reducing wear and tear, enhancing the overall performance and lifespan of the Jaipur Foot. Furthermore, UHMWPE's high molecular weight contributes to its exceptional durability, enabling it to withstand repetitive loading and impact without undergoing significant deformation or failure. This property ensures the longevity of the prosthetic limb, allowing individuals to engage in various physical activities with confidence.

The utilisation of both HDPE and UHMWPE in the Jaipur Foot highlights the careful consideration given to material selection to ensure the prosthetic limb's strength, wear resistance, and longevity. By incorporating these polyethylene variants, the Jaipur Foot strives to provide individuals with lower limb amputations a reliable and long-lasting solution that can withstand the demands of daily life.

The **processing technique** of HDPE and UHMWPE components for the Jaipur Foot involves specific techniques tailored to each material's characteristics.

For **HDPE**, the fabrication typically employs **injection moulding** or **compression moulding** techniques. In the injection moulding process, HDPE pellets are first heated to a molten state. The molten HDPE is then injected into a mould cavity, which is shaped to match the desired form of the component. As the injected material cools, it solidifies and takes on the shape of the mould cavity. This method allows for precise control over the dimensions and intricacies of the HDPE component.

In the case of **UHMWPE**, the processing technique usually involves **compression moulding** or **ram extrusion**. Compression moulding begins with UHMWPE powder being heated to a temperature that enables it to flow and become malleable. The heated UHMWPE is then placed between two mould halves and subjected to high pressure, which compresses and shapes the material into the desired component. The pressure applied ensures that the UHMWPE maintains its integrity during the cooling and solidification phase, resulting in a component with the desired characteristics.

Alternatively, ram extrusion may be employed in the processing of UHMWPE components. In this process, UHMWPE powder is fed into a chamber and subjected to high pressure using a ram or plunger mechanism. The pressure forces the UHMWPE through a die, which imparts the desired shape to the material as it extrudes. The extruded UHMWPE is then cooled and cut into the appropriate lengths to form the final component.

By utilising the appropriate manufacturing techniques for HDPE and UHMWPE, the Jaipur Foot ensures the production of components that meet the required specifications in terms of shape, strength, and functionality. These manufacturing techniques allow for the efficient and precise fabrication of the prosthetic limb's components, contributing to the overall quality and performance of the Jaipur Foot. [24]

Polypropylene, another significant material used in the construction of the socket of the Jaipur Foot, possesses specific properties that contribute to its suitability for the prosthetic limb.

One notable property of polypropylene is its excellent flexibility, which makes it well-suited for the articulating components of the Jaipur Foot. The flexibility of polypropylene allows for smooth and natural movements, facilitating a more comfortable and functional experience for the user. By incorporating polypropylene into the design of the articulating components, the Jaipur Foot aims to mimic the natural range of motion of the human foot, enhancing mobility and gait. Furthermore, polypropylene exhibits a lightweight nature, which is highly advantageous for the overall weight reduction of the prosthesis.

The incorporation of lightweight materials, such as polypropylene, contributes to the reduction of the Jaipur Foot's overall weight, resulting in enhanced user comfort and improved mobility. A lighter prosthesis reduces the strain on the residual limb, minimising fatigue and enabling individuals to engage in daily activities with greater ease. The flexibility and lightweight properties of polypropylene are vital considerations in the design and fabrication of the Jaipur Foot. By utilising this material, the prosthetic limb aims to provide users with optimal functionality, comfort, and mobility, allowing them to regain independence and participate actively in various physical activities.

Polypropylene, a key material used in the manufacturing of the Jaipur Foot, can undergo different **processing techniques** to achieve the desired shapes and components.

Injection moulding is a commonly employed method for processing polypropylene. In this process, polypropylene pellets are first melted at high temperatures to form a molten resin. The molten polypropylene is then injected under high pressure into a pre-designed mould cavity. Inside the mould, the polypropylene cools and solidifies, taking on the shape of the mould. Once solidified, the mould is opened, and the finished polypropylene component is ejected. Injection moulding allows for precise and efficient production of complex shapes and intricate details.

Extrusion is another technique used for processing polypropylene. In this method, the polypropylene resin is heated until it reaches a molten state. The molten polypropylene is then forced through a specially designed die, which imparts the desired shape. The extruded polypropylene emerges as a continuous profile, such as a rod or tube, and is then cooled and cut to the required lengths. Extrusion is particularly suitable for creating continuous shapes with consistent cross-sectional profiles.

By utilising either injection moulding or extrusion techniques, the Jaipur Foot ensures the precise fabrication of polypropylene components with the desired shapes and dimensions. These manufacturing processes allow for efficient production, enabling the Jaipur Foot to meet the functional and design requirements necessary for providing individuals with lower limb amputations with a prosthetic solution that is both effective and comfortable. [15]

Aluminium, an essential material which was utilised in the construction of the shank (part that connected ankle to the foot) or pylon of the Jaipur Foot. Nowadays HDPE is used in the manufacturing of the shank rather than aluminium. Aluminium offered a range of properties that contributed to its suitability for the prosthetic limb.

One key advantage of aluminium alloys was their favourable strength-to-weight ratio. Aluminium alloys provided excellent structural integrity while keeping the overall weight of the Jaipur Foot relatively low. This lightweight nature enhanced user comfort and mobility, reducing the strain on the residual limb and facilitating ease of movement. By incorporating aluminium into the design of structural components, the Jaipur Foot aimed to achieve a balance between strength and weight, ensuring durability without compromising functionality. In addition to its lightweight property, aluminium is also known for its corrosion resistance. The use of corrosion-resistant aluminium alloys ensured the longevity and reliability of the Jaipur Foot, even when exposed to moisture or other environmental conditions. This corrosion resistance helped to maintain the structural integrity of the prosthetic limb over time, reducing the need for frequent repairs or replacements. Furthermore, aluminium is easily machinable, allowing for precise shaping and fabrication of components. This machinability enabled the production of intricate and custom-designed parts for the Jaipur Foot, ensuring a proper fit and optimal functionality for the user. Additionally, aluminium exhibits good thermal conductivity, facilitating the dissipation of heat generated during movement, which helped prevent discomfort or overheating for the user. The properties of aluminium, including its favourable strength-to-weight ratio, corrosion resistance, machinability, and thermal conductivity, made it a valuable material for the construction of the Jaipur Foot.

By incorporating aluminium alloys, the prosthetic limb aimed to provide individuals with a durable, lightweight, and reliable solution, enabling them to regain mobility and independence.

The **processing technique** of aluminium components for the Jaipur Foot involves **casting** or **machining techniques**, tailored to the specific requirements of the prosthetic limb.

Casting methods, including sand casting, die casting, or investment casting, are commonly employed in the production of aluminium components. In sand casting, a pattern of the desired component is created, and a mould is formed around it using a mixture of sand and a binder. Molten aluminium is then poured into the mould, filling the cavity and taking the shape of the pattern. After solidification, the mould is removed, and the aluminium component is extracted. Die casting involves injecting molten aluminium under high pressure into a metal mould, resulting in precise and detailed components. Investment casting, also known as lost-wax casting, utilises a wax pattern that is surrounded by a ceramic shell. The wax is melted and drained, leaving behind a cavity that is filled with molten aluminium. Once cooled and solidified, the ceramic shell is removed, revealing the aluminium component.

Machining processes, such as **milling** or **turning**, are employed to shape and refine the aluminium components according to the desired specifications. In milling, a rotating cutting tool removes material from the aluminium workpiece to create the desired shape and surface finish. Turning involves rotating the aluminium workpiece while a cutting tool removes material to achieve the desired dimensions and shape. These machining techniques allow for precision and customization, ensuring that the aluminium components meet the specific requirements of the Jaipur Foot.

By employing casting or machining techniques, the Jaipur Foot ensures the accurate and efficient production of aluminium components. These techniques enable the creation of durable and precisely shaped parts, contributing to the overall quality and functionality of the prosthetic limb. [19]

HPEV (High-Performance Ethylene Vinyl Acetate) offers most useful quality for the Jaipur foot, that is its exceptional shock absorption properties. This quality is crucial for cushioning impact during walking, providing comfort to the user, and reducing the strain on the residual limb. By absorbing and dispersing the forces generated with each step, HPEV helps to minimize discomfort and fatigue, by serving as a soft lining between the prosthetic limb and the residual limb thereby enhancing the overall usability and effectiveness of the Jaipur foot prosthetic.

The processing techniques of HPEV involves moulding, extrusion and foaming.

For EVA, moulding techniques such as **compression moulding** or **injection moulding** are commonly used. In **compression moulding**, EVA pellets are placed in a heated mould, and pressure is applied to compress and shape the material. In **injection moulding**, molten EVA is injected into a pre-designed mould cavity, allowing for precise and efficient production of complex shapes. EVA's ease of processing makes it well-suited for moulding, enabling the creation of various components, from shoe soles to automotive parts.

Extrusion is commonly used to produce items like **EVA foam sheets**, **tubing**, or **profiles**. The molten EVA resin is pushed through the extrusion die, resulting in a continuous shape. EVA foam, often used for cushioning and padding, can be extruded into sheets or rolls with consistent cross-sectional profiles.

EVA can be foamed to produce **EVA foam**, which has excellent cushioning properties. During foaming, a chemical blowing agent or physical expansion process generates gas bubbles within the molten EVA. The resulting foam can be used in applications such as shoe insoles, yoga mats, and packaging materials. [8]

Wood, a unique material that was used in the shank (part that connects the ankle to the foot) and the foot, before being replaced by aluminium and rubber respectively in the construction of the Jaipur Foot. Wood possessed specific properties that contributed to its suitability for the prosthetic limb.

One notable advantage of wood is its excellent combination of strength, flexibility, and shock absorption. These properties made wood a suitable material for the foot component of the Jaipur Foot. Wood provides a natural level of resilience and cushioning, helping to absorb the impact forces generated during walking or other weight-bearing activities. This shock absorption capability enhanced user comfort and reduced the strain on the residual limb. Additionally, wood offered a balance between strength and flexibility, allowing for a controlled and responsive movement that mimicked the natural roll-over during walking. The inherent properties of wood contributed to the overall stability and gait of the Jaipur Foot.

In terms of the **processing techniques**, wood components for the Jaipur Foot were typically produced through a combination of **manual** and **machine processes**. The wood was carefully selected, and the required dimensions and contours are achieved through cutting, shaping, and carving techniques. Skilled craftsmen used their expertise to shape the wood components to meet the specific design requirements of the prosthetic limb. Techniques such as **lamination** and **glueing** might have been employed to enhance the strength and durability of the wood components. These processes ensured that the wood components possess the necessary structural integrity and functionality to withstand the demands of everyday use.

By incorporating wood into the design of the Jaipur Foot, the prosthetic limb aimed to provide individuals with a natural and comfortable walking experience. The combination of strength, flexibility, shock absorption, and the processing techniques tailored to wood components ensured that the Jaipur Foot met the biomechanical needs of users, promoting stability, gait, and overall mobility. [12]

Rubber materials, specifically synthetic elastomers, play a crucial role in the construction of the foot component of the Jaipur Foot, offering a range of properties that enhance its functionality and performance.

One significant advantage of rubber materials is their ability to provide cushioning and shock absorption properties. The use of rubber in the foot component helps to absorb impact forces generated during walking or running, reducing the strain on the user's residual limb. This cushioning effect enhances user comfort and helps to minimise the risk of injuries or discomfort associated with repetitive impact. The rubber materials used in the Jaipur Foot contribute to a smoother and more comfortable walking experience. Furthermore, rubber materials offer excellent grip and traction, contributing to improved stability and preventing slips or falls. The rubber sole of the Jaipur Foot provides a high coefficient of friction, enhancing the foot's contact with the ground and reducing the risk of losing balance on different surfaces. This grip capability is particularly essential for individuals with lower limb amputations, as it enhances their confidence and stability during various activities.

Regarding the **processing techniques**, rubber materials can be processed using various techniques, including **injection moulding**, **extrusion**, and **compression moulding**. In injection moulding, the rubber material is heated and melted, then injected into a mould cavity to form the desired shape. This method allows for precise shaping and intricate designs, ensuring that the rubber components of the Jaipur Foot meet the required specifications. Extrusion is used to create continuous rubber profiles, such as tubes or gaskets, by forcing the heated rubber material through a die of the desired shape. Compression moulding involves placing the rubber material into a heated mould and applying pressure until it takes the desired shape. These manufacturing techniques ensure the efficient production of rubber components for the Jaipur Foot, meeting the specific requirements of the prosthetic limb.

By incorporating rubber materials, specifically synthetic elastomers, into the design of the Jaipur Foot, the prosthetic limb aims to provide individuals with cushioning, shock absorption, grip, and traction. These properties contribute to user comfort, stability, and overall safety during various daily activities. [5]

ALTERNATIVE MATERIALS TO THOSE USED IN THE JAIPUR FOOT AND THEIR PROCESSING TECHNIQUES

In addition to the materials traditionally used in the Jaipur Foot, there are alternative materials that can be considered for certain components of the prosthetic limb. These alternative materials offer unique properties and advantages, providing potential improvements in performance and functionality.

For the rubber core, alternative materials to consider include silicone, latex, thermoplastic elastomer, or natural rubber. Silicone is known for its excellent flexibility, durability, and biocompatibility, making it suitable for cushioning and shock absorption purposes. Latex, thermoplastic elastomer, and natural rubber also offer similar properties and can provide cushioning and support to the foot component of the Jaipur Foot.

As for the vulcanised rubber coating, alternative materials include polyvinyl chloride (PVC), polyethylene, or synthetic leather. These materials offer durability, water resistance, and easy maintenance. PVC and polyethylene provide flexibility, while synthetic leather can offer a more aesthetically appealing and protective coating.

For the aluminium shank, alternative materials to consider are carbon fibre, fibreglass, or titanium. Carbon fibre is renowned for its exceptional strength-to-weight ratio, providing strength and lightweight characteristics. Fibreglass offers similar advantages, along with good flexibility and impact resistance. Titanium is another lightweight and durable material that provides excellent strength and corrosion resistance.

Silicone: Silicone is a versatile synthetic polymer that is composed of silicon, oxygen, carbon, and hydrogen. It is produced through a chemical reaction between silicon and methyl chloride, resulting in the formation of a liquid known as methyl chlorosilane. This liquid is then purified and hydrolysed to create a polymer called polydimethylsiloxane (PDMS). The properties of silicone can be further modified by incorporating different functional groups, allowing for the creation of various types such as elastomers, fluids, gels, or resins. Silicone materials offer exceptional heat resistance, electrical insulation properties, flexibility, and biocompatibility, making them suitable for a wide range of applications. They can be **moulded** into intricate shapes, **extruded** into tubes or profiles, or cured to form solid components. [20]

Latex: Latex is a natural polymer derived from the sap of rubber trees, primarily Hevea brasiliensis. To obtain latex, the bark of rubber trees is carefully tapped, allowing the milky sap to flow into collection containers. The collected latex is then processed to remove impurities and increase its solid content. **Coagulation** is typically achieved by adding acid or other coagulating agents, causing the latex to solidify into a mass of rubber. The coagulated rubber is washed, dried, and pressed into sheets or blocks. Latex-based materials offer excellent elasticity, resilience, and tear resistance, making them suitable for various applications such as gloves, balloons, and other elastic products. [1]

Synthetic leather: Synthetic leather, also known as faux leather or artificial leather, is a man-made material designed to replicate the look and feel of genuine leather. It can be produced using different materials, including polyurethane (PU), polyvinyl chloride (PVC), polyester, or nylon. Synthetic leather can be manufactured through various processes, such as **coating** a fabric base with a layer of plastic film or by **weaving** or **knitting** fibres together to form a nonwoven fabric. The material can then be embossed, dyed, or printed to create different textures, patterns, and colours. Synthetic leather offers advantages such as durability, water resistance, ease of maintenance, and a more affordable price compared to genuine leather.

It finds applications in various industries, including fashion, upholstery, automotive interiors, and footwear. [21]

Carbon fibre: Carbon fibre is a synthetic material made from thin strands of carbon atoms. It offers exceptional strength-to-weight ratio, high stiffness, and excellent resistance to temperature, chemicals, and fatigue. The production of carbon fibre involves several steps. Firstly, a precursor material, such as polyacrylonitrile (PAN) or rayon, is heated in an oxygen-free environment to carbonise the fibres, removing non-carbon elements and aligning the carbon atoms into long chains. The resulting carbonised fibres are then treated with surface agents and wound onto spools. To further enhance their strength and stiffness, the carbon fibres can be subjected to additional heating processes called graphitization, which restructures the carbon atoms into a more ordered form. Carbon fibres can be woven or braided into fabrics or combined with resin matrices to form carbon fibre composites, widely used in aerospace, automotive, sports equipment, and other high-performance applications. [23]

Fibreglass: Fibreglass is a composite material composed of glass fibres embedded in a resin matrix. The production of fibreglass involves melting glass and extruding it through fine holes to form thin filaments. These filaments are then coated with a binder and gathered into bundles called strands. Fibreglass strands can be chopped, woven, or sprayed onto a mould to form various shapes. The resin is then applied to the fibreglass and cured, resulting in a hardened material. Fibreglass offers good strength, flexibility, and electrical insulation properties. It is commonly used in industries such as construction, marine, automotive, and aerospace for applications including insulation, reinforcement, and structural components. [10]

Titanium: Titanium is a metallic element known for its high strength, low density, and excellent corrosion resistance. The production of titanium involves extracting it from its ore, such as rutile or ilmenite. The ore undergoes several chemical processes to convert it into titanium dioxide (TiO_2). Subsequently, the TiO_2 is reduced with magnesium or sodium in a reaction known as the Kroll process, resulting in the formation of a porous titanium sponge. The titanium sponge is then melted and cast into ingots or bars. These ingots or bars can be further processed through forging, rolling, or extrusion to produce various forms, including sheets, rods, tubes, or wires. Titanium is widely used in aerospace, medical implants, chemical processing, and other applications where a combination of high strength, low weight, and corrosion resistance is required.

By considering these alternative materials alongside the traditional ones used in the Jaipur Foot, designers and engineers have the opportunity to explore a wider range of options to improve the performance, comfort, and durability of the prosthetic limb. Each material offers its own unique set of properties, and further research and development are necessary to assess their suitability and optimise their integration into the design and manufacturing processes. [7]

DESIRABLE QUALITIES OF THE ALTERNATIVE MATERIALS

Alternative Materials Considered for the Foot

Silicone: Silicone is an elastomer that offers a wide range of properties suitable for various applications. Silicone exhibits high elasticity, low compression set, good thermal stability, and excellent resistance to weathering, ozone, and ageing. It can adhere well to various substrates and can be moulded into complex shapes, making it suitable for prosthetic components requiring flexibility, durability, and compatibility with the user's skin. [20]

Latex: Latex is a natural polymer derived from the sap of rubber trees. Latex exhibits high tensile strength, elongation, resilience, and tear resistance, making it suitable for applications where flexibility, shock absorption, and vibration damping are required. It can conform well to the shape of the user's limb, providing a comfortable fit for prosthetic components. [1]

Composite materials: Composite materials (**synthetic leather**) are made from two or more different materials that have distinct properties. By combining these materials, composite materials can exhibit improved mechanical, thermal, electrical, or optical properties compared to their individual components. Composite materials offer versatility in terms of tailoring their properties to meet specific design requirements and performance criteria. They can be engineered to have high strength, stiffness, and durability while maintaining a lightweight profile. [21]

Alternative Materials Considered for The Shank

Carbon fibre: Carbon fibre is a synthetic material that consists of thin strands of carbon atoms. It is known for its exceptional strength, stiffness, and modulus. Carbon fibre composites can have a high strength-to-weight ratio, making them suitable for applications where lightweight and robust materials are desired. Carbon fibre can be used as a reinforcement material in composite structures, providing superior strength and rigidity to prosthetic feet components. Additionally, carbon fibre exhibits excellent corrosion resistance, making it suitable for prosthetic applications where exposure to moisture or harsh environments is expected. [23]

Fibreglass: Fibreglass is a composite material made from glass fibres embedded in a resin matrix. The glass fibres provide strength and reinforcement, while the resin matrix holds them together and transfers loads. Fibreglass composites offer a combination of strength, stiffness, and durability. They can be moulded into various shapes and sizes, making them versatile for prosthetic foot applications. Fibreglass composites are widely used in industries where lightweight and cost-effective materials are required. [10]

Titanium: Titanium is a metallic material that possesses high strength, low density, and excellent corrosion resistance. It is widely used in various industries, including aerospace and medical applications. Titanium offers a favourable strength-to-weight ratio, making it suitable for prosthetic foot components that require structural integrity without adding excessive weight. It can withstand high temperatures and fatigue loads, ensuring long-term durability and reliability. Titanium can be machined or formed into desired shapes, allowing for precise customization of prosthetic components. [7]

These alternative materials provide a range of properties and characteristics that can be utilised in the design and manufacturing of prosthetic feet. The selection of the appropriate material depends on factors such as desired performance, weight considerations, durability, and cost-effectiveness, among others. By exploring different materials and their properties, prosthetic foot designers and manufacturers can enhance the functionality, comfort, and overall quality of prosthetic devices for individuals in need.

Table 1 Material Specifications [3]

Material	Density (kg/m3)	Tensile strength (MPa)	Elongation (%)	Young's Modulus (GPa)	Yield Strength (MPa)
Wooden block (obsolete)	500-700	50-100	1-5	0.5-3	2-6
Rubber core	920-930	3.5-3.9	500-800	0.0015-0.0025	20-30
Alternatives for the foot component of the Jaipur Foot					
Silicone	1300-1800	11-13	100-900	0.005-0.022	2.4-5.5
Latex	920-930	20-30	700-900	0.0015-0.0025	20-30
Synthetic leather	Varies depending on components and composition				
Aluminium shank (obsolete)	2700	200-500	5-15	68-82	30-500
Alternatives for the shank component of the Jaipur Foot.					
Carbon fibre (composite)	1500-2000	1000-3000	1-2	69-150	550-1100
Fibreglass (composite)	1800-2200	300-800	2-4	15-28	110-190
Titanium (metal)	4500	500-900	10-20	90-120	250-1200
Iron Alloy (for pylons in above knee)	7600-8100	480-2200	30-40	190-210	170-220
Polyethylene (PE, for sockets and shanks)	940-960	10-40	100-600	0.62-0.9	18-29 [3]

Future Prospects and Research Gaps

The reviewed literature has provided valuable insights into the materials used in the Jaipur Foot, but there are several future prospects and research gaps that deserve further attention and exploration. By addressing these areas, we can advance the field of prosthetics and enhance the mobility, comfort, and quality of life for individuals with lower limb amputations.

Advanced Material Optimization: One area of focus for future research is the optimization of the properties of existing materials used in the Jaipur Foot. While the current materials have demonstrated their effectiveness, there is room for improvement. Exploring advanced processing techniques, such as additive manufacturing or composite fabrication methods, can enhance the mechanical properties, durability, and weight reduction of the prosthetic components. By fine-tuning the composition and structure of these materials, we can achieve even better performance and functionality. Another direction that could be explored is the cost effectiveness of the alternative materials mentioned in this paper, as cost effectiveness remains the main reason for current manufacturing practices of the Jaipur Foot.

Biocompatible and Sustainable Materials: Another promising direction for research is the development of biocompatible and sustainable materials for the Jaipur Foot. Although the current materials exhibit good biocompatibility, further studies can focus on exploring bioresorbable or biodegradable materials that integrate with the body's tissues over time. This can help reduce the need for frequent replacements and improve long-term comfort and functionality. Additionally, investigating the use of recycled or environmentally friendly materials aligns with sustainable practices and reduces the environmental impact of prosthetic production.

Interface and Socket Design: The interface between the residual limb and the socket of the Jaipur Foot is a critical aspect that deserves attention. Research should be directed towards improving the comfort, breathability, and pressure distribution of the interface materials to minimise discomfort and skin issues. Enhancing the fit and function of the socket through advanced design approaches, such as adjustable or **adaptive sockets**, can greatly enhance user comfort and overall satisfaction. By considering the user's biomechanics and individual needs, we can create a more seamless and comfortable connection between the residual limb and the prosthetic device.

Long-Term Durability and Performance: It is essential to conduct long-term durability studies to assess the performance and longevity of the Jaipur Foot over extended periods of use. Understanding the effects of wear and tear, environmental conditions, and user activities on the materials' integrity can guide design improvements and ensure sustained functionality. By conducting comprehensive durability tests and monitoring the performance of the prosthetic components over time, we can identify areas for enhancement and develop materials that can withstand the rigours of daily use.

By addressing these future prospects and research gaps, we can advance the field of prosthetics and contribute to the continuous improvement of the Jaipur Foot.

CONCLUSION

In conclusion, the materials used in the Jaipur Foot are carefully selected based on their specific properties to ensure that the prosthetic meets the necessary biomechanical requirements. Each material plays a crucial role in contributing to the overall functionality, comfort, and durability of the prosthesis.

Polyethylene is chosen for load-bearing components like the foot and ankle due to its strength, wear resistance, and low friction properties. These characteristics enable it to withstand the forces exerted during walking and provide a smooth articulation for natural movement.

Polypropylene is valued for its flexibility and lightweight nature, which contribute to the articulation and overall weight reduction of the prosthesis. Its ability to provide a comfortable and dynamic response during gait is instrumental in ensuring a more natural walking experience.

Aluminium was utilised for its excellent strength-to-weight ratio, providing structural integrity while keeping the prosthesis lightweight. Its corrosion resistance and machinability make it suitable for the fabrication of various structural components, ensuring durability and longevity.

Wood is a unique material which was used in the foot section of the Jaipur Foot, offering a combination of strength, flexibility, and shock absorption properties. These qualities enable a natural roll-over during walking, enhancing the overall gait pattern and providing a comfortable walking experience.

Rubber materials, such as silicone and latex, are incorporated into the design of the Jaipur Foot to provide cushioning, shock absorption, and grip. These materials contribute to stability, prevent accidents, and improve the overall safety and functionality of the prosthetic.

The processing techniques associated with each material, including injection moulding, compression moulding, extrusion, casting, machining, and wood carving, are carefully employed to fabricate components with precise shapes and desired mechanical properties. These processes ensure optimal performance and functionality, meeting the specific requirements of the Jaipur Foot.

In conclusion, the materials and manufacturing processes employed in the Jaipur Foot are the result of extensive research and engineering to create a prosthetic that not only mimics the natural function of the lower limb but also enhances the mobility and quality of life for individuals with lower limb amputations. By considering the unique properties of each material and employing advanced manufacturing techniques, the Jaipur Foot represents a significant advancement in prosthetic technology. Continued research and innovation in material science and design will further improve the performance, comfort, and accessibility of prosthetic solutions for individuals worldwide.

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