Prosthetics: Challenges and Innovations: A Literature Review

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Received 01.08.2025 **received in revised form** 08.05.2026, **accepted** 12.05.2026
DOI: 10.47904/IJSKIT.16.1.2026.108-111

Abstract- Due to the loss of the knee-joint and associated musculature, transfemoral amputation, commonly known as above-knee amputation, presents significant biomechanical and functional challenges. This paper investigates the causes, clinical considerations, and post-operative rehabilitation strategies for transfemoral amputees. The biomechanics of single-axis versus polycentric four-bar prosthetic knee joints are compared in this study, considering applications to various user profiles. The study investigates the selection of compatible & innovative material for prosthetic components in developed and developing nations. In general, the review emphasizes context-specific prosthetic design with materials that will enhance the affordability of the prosthetics while improving the functionality related to the quality of life of transfemoral amputees in India.

Keywords-- Transfemoral Amputation, Above Knee Prosthesis, Polycentric Knee Joint, Prosthetic Materials, Thermoplastics, Titanium Alloys, Passive Prosthesis, Active Prosthesis

1. INTRODUCTION

It can be observed that standing plays an important role in enabling everyday life and maintaining quality of life among individuals with lower limb amputation. As per the Census of India in 2011, around 2.32 % of the country's population, which is about 27.9 million people, are identified as 'disabled,; out of these, nearly 20% have movement-related disabilities [1]. The causes for lower limb amputation may be due to (i) accidents on road (ii) wartime hurts, (iii) vascular and diabetic complications, (iv) malignant tumor growth, and (v) congenital deformity observed at birth. Lower limb amputation types will depend on the severity and nature of the condition, which usually consists of Transtibial, Transfemoral, Knee disarticulation, Hip disarticulation, Partial foot, and Ankle disarticulation. Sometimes, expensive materials like titanium alloys, carbon fiber composites, and advanced polymers are used based on strength-to-weight ratio and load-bearing capacity or fatigue resistance. In contrast, low-cost alternatives like thermoplastics and nylons dominate resource-poor regions, despite some sacrifices in durability and performance. Moreover, the development of passive and active prostheses is reviewed, including the increasing use of microprocessor-controlled and sensor-integrated devices to improve gait efficiency.

2. TRANSFEMORAL AMPUTATION

Maxime Acien et al. conducted a systematic search across databases of resources employing biomechanics, functional tests (Functional Reach Test) and assessments of balance confidence and physical performance. For effective rehabilitation post-transfemoral amputation, surgical procedures must preserve the maximum length of the residual limb, maintain adductor muscle integrity, and ensure proper suturing of soft tissues to minimize scarring [2-3].

The findings of the study of Ben Langley et al. reveal sensitivity of the body posture, its independence from movement velocity and the association with joint factors. It can be seen that the developed metric application can improve the assessment of human body musculoskeletal function [4].

Accroding to D. Smith et al., transfemoral amputees encounter significant functional limitations, including instability, discomfort during the sitting, difficulty during the rising from a chair, and higher dynamism demands during mobility [5], as shown in figure-1. These people often face challenges engaging in day-to-day activities and sports. Although younger amputees adapt more freely to prosthetic use, older individuals frequently struggle with the increased energy requirements.

3. PROSTHETICS AND REHABILITATION

The term "prosthetics" originates from the Ancient Greek word meaning "to add" [6]. In orthopedics, a prosthesis refers to an artificial limb that replaces an amputated extremity [7]. It can be seen in medical science that the lower limb prostheses are essential for restoring mobility and social participation. While replicating the full function of a natural limb remains technologically unfeasible due to its biological complexity, a well-designed prosthesis can offer sufficient mobility, comfort, and independence to amputees. It is widely acknowledged that an ideal prosthetic device must enable a natural gait and be both physically and psychologically acceptable to the knee joint patients.

In the medical science, two primary categories of prostheses are used depending on the site of amputation: below-knee and above-knee prostheses.

4. TRANSFEMORAL (ABOVE-KNEE) PROSTHESIS

In transfemoral amputation cases, the artificial limb is referred to as a transfemoral or above-knee prosthesis. This device should allow user to control the artificial knee using the residual limb. Two fundamental types of transfemoral prostheses exist: exoskeletal and endoskeletal (Figures 1(a) and 1(b)). Exoskeletal models feature a rigid outer shell made of laminated plastic or wood with foam interiors, while endoskeletal designs consist of a modular system including a socket, knee joint, pylon, and foot.

The knee joint is the critical component of an above-knee prosthesis, as it must replicate lost muscular functions, especially for stability during stance and controlled movement during the swinging posture [8]. The human knee is a complex joint formed by four bones: the femur, tibia, fibula, and patella.

Despite the availability of over 100 commercial designs, knee joints are generally categorized into single-axis and polycentric types [9]. Single-axis knees rotate around a fixed center, whereas

polycentric designs combine rotation and translation through an "instantaneous center of rotation". Single-axis knees require the user to keep the knee fully extended during weight-bearing, often leading to unnatural gait patterns and associated physical stress. Conversely, four-bar polycentric designs offer superior stability during heel strike, reduced energy demands, better voluntary control, and a shorter prosthetic length during the swing phase [10]. These advantages have made the four-bar design a popular choice among amputees.

5. MATERIAL SELECTION IN PROSTHETIC KNEES

5.1. Developed Countries

In developed nations, the selection of materials for prosthetic knees prioritizes mechanical performance over cost. Ideal materials are those offering high strength, low density, excellent fatigue resistance, and corrosion protection. Common choices include titanium alloys, stainless steel, high-strength aluminum alloys, and carbon fiber composites. Additionally, some components use polymers or copolymers for their self-lubricating and low-friction characteristics. These high-end materials contribute significantly to the overall cost of prostheses, which may often amounting to high prices.

5.2. Developing Countries

In contrast, cost is a critical issue in material selection in India, where many amputees live below the poverty line. It can be observed that locally available and low-cost thermoplastics are predominantly used due to their light weight, ease of machining, and low value of frictional coefficient. These low cost materials include nylon, polyacetal, polypropylene, and polyethylene. Despite being cost-effective, these polymers generally offer inferior mechanical strength and wear resistance compared to metal alloys. As a result, some prosthetic components are prone to failure under repetitive loading during daily activities. There is, therefore, an urgent need to develop materials that combine low cost with superior wear resistance and mechanical durability.

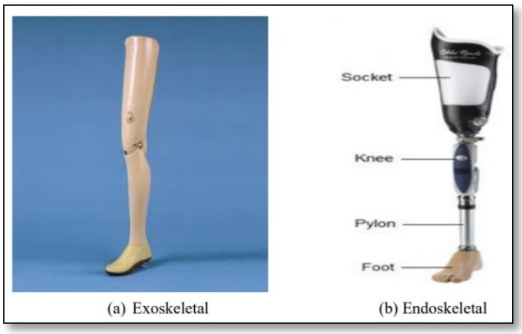

Figure 1: Transfemoral Prosthesis [2]

6. PASSIVE VS. ACTIVE PROSTHESES

6.1. Passive Prostheses

Passive prostheses function by storing energy during the heel strike phase and releasing it during toe-off. This energy mechanism is often achieved using spring systems. However, passive devices tend to require high energy expenditure during walking, reducing their usability among amputees [11]. A well-designed passive knee prosthesis can minimize this energy cost. Popular mechanical designs include manually locking knees, polycentric knees, and weight-activated stance control knees, which operate without microprocessor input.

6.2. Active Prostheses

Low-cost prostheses generally lack advanced features for aiding gait during the swing phase. Swing-phase control knees help limit heel rise, support knee extension, and soften impact at terminal extension, leading to a smoother and more efficient gait . In active prostheses, microprocessors monitor and control joint movements using input from various sensors that track stride length, speed, and applied force. These systems attempt to replicate the dynamics of a healthy limb. Actuation is achieved using hydraulic, pneumatic, or electric motors. Among them, pneumatic systems offer precise control and sufficient power for prosthetic applications [12].

7. MATERIALS IN PROSTHETIC DEVELOPMENT

7.1. Metals

Metals such as hard-aluminum, steel, fine and micro - titanium, magnesium, and copper are widely used in prosthetic components. Aluminum is preferred for its lightweight properties, while steel is used in smaller parts. Titanium is increasingly favored due to its biocompatibility, corrosion resistance, lightness, and non-magnetic properties. Often, titanium is alloyed with aluminum and vanadium to enhance its strength and durability.

7.2. Plastics

Recent years have seen a shift from traditional materials like wood and leather to thermoplastics and composites . These materials offer low density, ease of molding, corrosion resistance, and improved fatigue and shock absorption . Since the 1960s, polyethylene and polypropylene have been extensively used in both prosthetics and orthotics. Thermoplastics are commonly found in long-leg braces (KAFOs) and spinal orthoses. Polypropylene is particularly beneficial in below-knee and transfemoral sockets due to its lightweight and low energy demands.

Over the past five decades, High-Molecular-Weight Polyethylene has emerged as one of the most widely used materials for artificial replacements in clinical settings. It is particularly favored in arthroplasty applications, especially for hip and knee joint implants, due to its excellent wear resistance and biocompatibility [13-15]. In low-cost prosthetic systems such as the Jaipur knee, oil-impregnated nylon is employed as a key material. The presence of oil within the nylon matrix reduces friction at the bearing surfaces, thereby enhancing wear resistance and eliminating the need for external lubrication. According to C. Chung et al. oil impregnation lowers moisture absorption. It was observed that the material faces limitations including poor stability at high temperatures, flammability, and increased wear and high friction under high load situations [16].

V. Kumar and D. K. Pratihar observed that the Nylon sheaths and stockings have been traditionally utilized in prosthetic applications for their flexibility and ease of wear. Another advanced polymer, Polyether-Ether-Ketone (PEEK), is increasingly being adopted in both fixed and removable prosthetic applications, particularly in spinal and orthopedic implants, and has demonstrated potential in dental prosthetics as well [17]. W. Liang *et al* used the composite prosthetic structures, plastic polymer laminates which were used to bond layers of carbon fiber, fiberglass, and nylon, providing enhanced strength and fatigue resistance [18]. Similarly, researcher M. Meng et al. used thermoset polymers like acrylics, epoxies, and polyesters which frequently employed in the fabrication of prosthetic sockets due to their high dimensional stability and molding characteristics [19].

8. CONCLUSION

This review has highlighted the current state of above-knee, prosthetics by focusing on the clinical, mechanical, and material aspects defining their design and functionality. Transfemoral amputations result in difficult rehabilitation challenges with regard to impaired knee function, high energy needs, and limited mobility. It can be seen by reserchers that the appropriate surgical procedures combined with the preservation of the residual limb and personalized prosthetic design will contribute to successful rehabilitation.

Recent studies have also emphasized the growing role of artificial intelligence and smart design approaches in improving prosthetic compatibility, gait performance, and patient-specific customization. Furthermore, advances in osseointegrated prosthetic systems are opening new possibilities for enhanced stability, comfort, and long-term functional outcomes in transfemoral amputees [20-21].

The evolution of basic exoskeletal to advanced endoskeletal systems has helped ensure greater comfort and control for users. Other types of passive prosthetics, such as polycentric knees, which offer improved stability, have also become common in low-resource settings around the world. In contrast, active prostheses are now allowing near-natural gait dynamics through the use of microprocessor-controlled systems, hydraulic/pneumatic actuators, and sensor-based feedback.

Material selection continues to be a crucial factor: for performance, established economies use high-strength alloys such as titanium and composites, while developing regions continue to utilize cost-effective thermoplastics like polypropylene and oil-filled nylons. Increased utilization of polymers such as PEEK and high-molecular-weight polyethylene in prosthetic parts mirrors improvements in biocompatibility, friction resistance, and user safety.

Despite such progress, challenges in the form of mechanical wear, structural fatigue, and inaccessibility due to economic weakness still persist. Any future work needs to be affordable, durable, and bio-integrated with the context of the socio-economic background where it is applied. Sustainable materials, intelligent control, and user-centric design will make the bridge between need and accessibility in developing and developed nations.

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