Bridging Performance and Affordability: Advances and Challenges in Modern Prosthetic Foot Development

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ABSTRACT
Prosthetic foot technology has undergone remarkable advancements, evolving from rigid, non-articulated designs such as the solid ankle cushioned heel (SACH) foot to dynamic-response, microprocessor-controlled, and bionic models that closely mimic the biomechanics of the natural ankle–foot complex. These innovations have significantly improved gait restoration, reduced energy expenditure, enhanced balance, and positively influenced psychosocial outcomes. However, accessibility remains a critical challenge: while advanced designs deliver superior therapeutic and functional benefits, their high cost and technical complexity limit availability in low- and middle-income countries (LMICs). Conversely, low-cost models such as the Jaipur Foot, Niagara Foot, and MIT prosthetic foot provide culturally adaptable and affordable solutions, though often with reduced biomechanical sophistication. This review synthesizes current knowledge on prosthetic foot classification, design principles, therapeutic outcomes, and affordability challenges. It highlights the trade-offs between performance and cost, drawing attention to global disparities in prosthetic availability and use. Emerging trends including robotics artificial intelligence, personalized and adaptive solutions sustainable materials, and 3D printing offer opportunities to bridge the gap between high performance and universal accessibility. Addressing these challenges requires interdisciplinary collaboration across engineering, clinical rehabilitation, and global health. By balancing innovation with affordability, the next generation of prosthetic foot technology has the potential to deliver equitable mobility solutions for amputees worldwide.

Keywords: Prosthetic foot, energy storage and return, microprocessor-controlled prosthesis, affordability, accessibility.

INTRODUCTION

Lower-limb amputation remains a major clinical intervention worldwide, often necessitated by trauma, peripheral vascular disease, diabetes, malignancies, or congenital anomalies. Globally, millions of individuals live with limb loss, with the incidence rising in parallel with non-communicable diseases such as diabetes and cardiovascular conditions. Amputation not only restricts mobility but also profoundly affects an individual's independence, psychological well-being, and socioeconomic participation. Prosthetic rehabilitation serves as the cornerstone of post-amputation care, with the prosthetic foot functioning as the critical interface between the user and the ground. Its role extends beyond replacing lost anatomy; it is central to restoring ambulation, stability, and energy efficiency during gait. The design and functionality of the prosthetic foot are therefore pivotal in determining clinical outcomes and overall quality of life for amputees.

Prosthetic feet were simple, rigid structures primarily aimed at providing basic weight-bearing support. Early designs, such as wooden blocks or rudimentary leather assemblies, allowed only limited mobility and lacked biomechanical sophistication. The introduction of the Solid Ankle Cushioned Heel (SACH) foot in the mid-20th century represented a significant advance, offering shock absorption at heel strike and a more natural rollover during walking. However, its limitations in energy storage and return restricted functionality for active users. Subsequent decades witnessed progressive improvements driven by advancements in materials science, biomechanics, and engineering. Elastic keel and dynamic-response feet emerged, incorporating flexible polymers and carbon composites that enabled energy storage and return (ESR) mechanisms. These designs enhanced walking efficiency, reduced stress on the sound limb, and supported higher activity levels. The evolution further expanded with articulated feet, including single- and multi-axis models, which improved adaptability on uneven terrain and enhanced user stability.

In recent years, the integration of microprocessors, sensors, and robotics has revolutionized prosthetic foot technology. Microprocessor-controlled feet can adapt in real time to changes in walking speed, terrain, and user activity, offering a level of responsiveness closer to the natural ankle-foot complex. Concurrently, the emergence of affordable, ruggedized designs such as the Jaipur Foot and MIT's low-cost prosthetic foot reflects growing attention to accessibility, particularly in low- and middle-income countries (LMICs). Thus, the trajectory of prosthetic development reveals a dual challenge: to optimize biomechanical performance while ensuring affordability and accessibility across diverse global populations.

Given the diverse landscape of prosthetic foot technology, ranging from low-cost conventional models to advanced microprocessor-controlled systems, there remains a pressing need to synthesize existing evidence on both performance outcomes and affordability challenges. This review aims to bridge these two dimensions by critically analysing advances in prosthetic foot design, therapeutic benefits, and the socioeconomic implications of accessibility.

Specifically, the objectives of this review are to:

- Examine the classification, types and engineering design of prosthetic feet, highlighting their biomechanical and functional attributes.
- Evaluate therapeutic and functional outcomes, including gait restoration, energy expenditure, and quality-of-life impacts.
- Discuss the challenges of affordability and accessibility, with emphasis on innovations tailored to resource-limited settings.
- Provide a comparative analysis of prosthetic foot categories, drawing attention to trade-offs between performance and cost.
- Identify emerging trends and future directions in prosthetic foot development, including robotics, artificial intelligence and sustainable design approaches.

By bringing together perspectives from clinical rehabilitation, engineering innovation, and global health, this review underscores the necessity of balancing performance and affordability in order to create prosthetic solutions that are both technologically advanced and universally accessible.

CLASSIFICATION OF PROSTHETIC FEET

The prosthetic foot is the most critical component of lower-limb prostheses, as it dictates the efficiency of gait restoration, stability, and user comfort. Over the decades, prosthetic feet have been classified according to structure, function, and technological sophistication. This section outlines the major categories, from traditional non-articulated feet to advanced microprocessor-controlled systems, highlighting their biomechanical attributes, advantages, and limitations.

Non-Articulated Feet

Conventional Feet: Conventional prosthetic feet are the most basic designs, primarily offering support for standing and walking at low activity levels. They are rigid and inexpensive, but they lack mechanisms for energy storage, shock absorption, or adaptive mobility. As such, they are usually prescribed for elderly amputees, new prosthetic users, or individuals with limited mobility needs.

Solid Ankle Cushioned Heel (SACH) Foot: The SACH foot, introduced in the mid-20th century, marked a significant innovation over traditional wooden block. It consists of a rigid internal keel embedded in a foam or rubber body, with a cushioned heel wedge to absorb impact at heel strike. The SACH design provides stability during mid-stance and mimics ankle plantar flexion through heel compression. Despite its durability, low cost, and minimal maintenance requirements, the SACH foot is limited by low energy return and inability to adapt to uneven terrain, making it suitable only for users with low activity levels.

Elastic Keel Foot: The elastic keel foot evolved as an improvement over the SACH design. Its flexible forefoot keel allows smoother rollover and better accommodation of uneven ground. By storing small amounts of energy during stance and releasing it during toe-off, the elastic keel foot offers slightly improved gait dynamics compared to SACH. However, it remains limited in terms of energy efficiency and performance for active users.

Articulated Feet

Single-Axis Foot: Single-axis prosthetic feet incorporate a hinge joint that allows dorsiflexion and plantar flexion. This feature improves knee stability during stance and facilitates smoother transitions between gait phases. The design also permits controlled motion using bumpers or springs, which absorb shock at heel strike. While effective for enhancing stability, single-axis feet are heavier and prone to mechanical wear compared to non-articulated designs, and they lack lateral motion.

Multi-Axis Foot: Multi-axis feet allow movement across several planes, including dorsiflexion, plantar flexion, inversion, and eversion. This multidirectional mobility enhances adaptability to uneven terrain, reduces stress on the residual limb, and improves user comfort. They are especially beneficial for active community ambulators who frequently encounter varied walking environments. However, multi-axis designs tend to be heavier, more expensive, and less durable, requiring careful maintenance.

Dynamic Response & Energy Storage and Return (ESR) Feet

Dynamic response, or ESR feet represent a substantial leap in prosthetic technology. Constructed from carbon fibre composites or other advanced polymers, these feet function as springs: they store energy during stance and release it during toe-off, mimicking the function of the biological ankle-foot complex. ESR feet reduce metabolic cost of walking, improve gait symmetry, and protect the contralateral limb from overuse injuries.

Early ESR designs, such as the Seattle Foot and SAFE foot, introduced the principle of dynamic energy return. Modern versions, including Flex-Foot Cheetah and Vari-Flex, provide superior energy storage, enabling higher speeds, running, and sports participation. Despite these benefits, ESR feet remain expensive and require technical expertise for fitting, limiting their accessibility in low-resource settings.

Microprocessor-Controlled and Bionic Feet

Recent advances in mechatronics and robotics have enabled the development of microprocessor-controlled (MPC) and bionic feet. These devices integrate sensors, actuators, and embedded computers to continuously monitor user activity and adapt foot response in real time. Adjustments in damping resistance, ankle angle, and gait dynamics provide a more natural walking experience and reduce the risk of falls, especially on slopes and uneven surfaces. Bionic feet can actively generate powered motion, enhancing push-off during gait. This capability offers significant benefits for active users, including athletes, and for individuals with higher functional levels (K3–K4). However, MPC and bionic feet are associated with high costs, battery dependence, and susceptibility to technical failures. Their accessibility is therefore restricted primarily to high-income settings.

Low-Cost Prosthetic Feet for Resource-Limited Settings

In many low- and middle-income countries (LMICs), affordability and accessibility are the primary barriers to prosthetic care. Traditional designs like the Jaipur Foot in India, Niagara Foot in Canada, and MIT's low-cost prosthetic foot have been developed specifically to address these needs. Such designs prioritize durability, cosmesis and adaptability to local environments (e.g., barefoot walking, squatting, or working in agricultural fields).

These low-cost models are often constructed from locally available materials such as vulcanized rubber, polymers, or composite plastics. Advances in 3D printing are also emerging as a cost-effective manufacturing approach, enabling customization at reduced expense. Although these feet may not match the biomechanical sophistication of ESR or MPC designs, they play a vital role in improving mobility and quality of life for millions of amputees worldwide.

DESIGN AND ENGINEERING ASPECTS

The design of a prosthetic foot requires a careful balance between biomechanics, material selection, durability, and user needs. Each engineering decision—whether related to structure, material, or integration with the rest of the prosthesis—directly influences the clinical performance, comfort and longevity of the device.

Materials Used in Prosthetic Foot Manufacturing

Material choice plays a defining role in prosthetic foot performance. Traditionally, wood and leather were widely used due to availability and low cost, though these lacked durability and biomechanical sophistication. With advances in polymer science, polyurethane, thermoplastics, and elastomers became common, offering flexibility, cushioning and resistance to wear.

Modern prosthetic feet increasingly employ composite materials, particularly carbon fiber, due to their high strength-to-weight ratio and superior energy storage capacity. Carbon fiber laminates enable dynamic-response and ESR designs that store elastic energy during stance and release it during push-off, closely replicating the function of the biological ankle-foot complex. Other advanced polymers, such as Kevlar-reinforced composites and silicone blends, provide a balance of durability, cosmesis and comfort.

For low-cost prostheses in resource-limited regions, rubberized materials, recycled plastics, and locally available composites are used. These ensure affordability and repairability, although they often compromise performance compared to high-end composites.

Biomechanical Design Considerations

The prosthetic foot must replicate essential biomechanical functions of the natural foot and ankle, including shock absorption, dorsiflexion, plantar flexion, inversion, and eversion.

Shock absorption is critical during heel strike, reducing the impact transmitted to the residual limb and contralateral joints. Designs such as the SACH foot achieve this through cushioned heels, while modern ESR feet rely on composite flexibility.

Dorsiflexion and plantar flexion allow smoother rollover and stability during stance. Articulated designs (single-axis or multi-axis feet) incorporate hinge mechanisms and bumpers to mimic these movements.

Mediolateral control (inversion and eversion) is necessary for stability on uneven terrain. Multi-axis designs address this need, while non-articulated feet lack this adaptability.

These biomechanical considerations are essential for ensuring natural gait, reducing metabolic cost of walking, and preventing overuse injuries of the intact limb.

Energy Return and Gait Cycle Dynamics

One of the most important design objectives is replicating the energy storage and return (ESR) function of the natural ankle-foot complex. During gait, the biological foot stores elastic energy in tendons and muscles during stance and releases it during push-off. Prosthetic feet attempt to mimic this through flexible keels and carbon fiber composites.

Dynamic-response feet (e.g., Flex-Foot Cheetah) act as mechanical springs: compressing under body weight, storing energy, and releasing it as propulsion. This reduces energy expenditure, improves walking speed, and enhances mobility for active users.

The gait cycle dynamics of a prosthetic foot are influenced by factors such as keel stiffness, rollover shape, and effective foot length. An optimized rollover curve ensures smooth weight transfer and minimizes deviations from natural gait. Advanced designs integrate gait-sensing algorithms and microprocessors, allowing adaptive energy return across varying terrains and speeds.

Durability, Fatigue Testing, and Standards (ISO, ASTM)

Durability and safety are critical in prosthetic design. Prosthetic feet are subjected to repetitive mechanical loading, equivalent to millions of gait cycles throughout their lifespan. Fatigue failures, material degradation, and wear can compromise user safety and increase maintenance costs.

International standards ensure consistent testing and quality assurance:

- ISO 10328 defines structural testing protocols for lower-limb prostheses, simulating walking loads to evaluate strength and fatigue resistance.
- ASTM standards provide guidelines for material testing, including impact strength, elasticity, and resistance to environmental factors.

Durability tests often include fatigue machines that replicate heel strike and toe-off loading under cyclic stresses. High-performance ESR and microprocessor feet undergo rigorous testing to ensure long service life, whereas low-cost designs are tested primarily for basic reliability and ruggedness in diverse environments.

THERAPEUTIC AND FUNCTIONAL OUTCOMES

The ultimate measure of a prosthetic foot is not only its engineering sophistication but also its therapeutic value and functional impact on users. While material innovations and mechanical refinements are vital, their true success is reflected in improved gait biomechanics, enhanced physiological efficiency, psychosocial well-being, and suitability across varied activity levels. This section explores these outcomes in detail.

Biomechanical Performance and Gait Restoration

Restoration of natural gait is one of the primary objectives of prosthetic foot design. A well-designed prosthesis should approximate the kinematics and kinetics of the intact ankle-foot complex, enabling smoother transitions across gait phases.

Non-articulated designs such as the SACH foot provide stability during stance but often lead to stiff, asymmetric gait patterns due to limited motion and low energy return. By contrast, dynamic response feet (ESR) improve gait symmetry by mimicking the spring-like action of tendons, thus reducing compensatory movements in the contralateral limb. This decreases abnormal joint loading and lowers the long-term risk of osteoarthritis.

Articulated and multi-axis feet contribute to more natural rollover and adaptability on uneven terrain, reducing the likelihood of stumbling. Microprocessor-controlled feet take gait restoration further by adjusting resistance and ankle angles in real time, providing a level of biomechanical fluidity that closely mirrors biological function.

Physiological Benefits: Balance, Energy Expenditure, and Mobility

Beyond gait mechanics, prosthetic feet have significant implications for the physiological demands of walking. Amputees typically expend more energy than able-bodied individuals due to altered biomechanics and reduced push-off power. Prosthetic feet that incorporate energy storage and return mechanisms effectively reduce this metabolic burden, enabling longer walking distances and improved endurance.

Balance and postural stability are also critical therapeutic outcomes. Multi-axis and microprocessor-controlled feet offer improved stability by adjusting to surface irregularities, thereby reducing falls and enhancing user confidence. Shock absorption features in certain designs lessen the impact on the residual limb, protecting soft tissues and preventing discomfort during prolonged ambulation.

Mobility gains extend beyond walking efficiency. Advanced feet enable amputees to navigate slopes, stairs, and uneven terrain more effectively. This expands participation in daily activities, occupational tasks, and recreational pursuits, directly influencing independence and social reintegration.

Psychosocial and Quality-of-Life Impacts

The psychosocial dimension of prosthetic foot use is equally important. Limb loss often leads to reduced self-esteem, depression, and social withdrawal. Effective prosthetic rehabilitation mitigates these effects by restoring independence, mobility, and body image.

Low-cost feet such as the Jaipur Foot play a particularly significant role in low- and middle-income countries, where the ability to walk, squat, or perform culturally relevant activities has profound implications for dignity and social participation. Conversely, advanced ESR and microprocessor-controlled feet enhance confidence among high-activity users, enabling them to engage in professional, athletic, or community roles with fewer limitations.

Quality of life assessments consistently highlight improvements in domains such as mobility, social engagement, and psychological resilience among prosthetic users. However, disparities in access remain a barrier: while advanced designs deliver superior performance, their high cost often excludes many amputees, particularly in resource-limited settings.

Sports, Rehabilitation and High-Activity Users

For athletes and highly active individuals, the demands on prosthetic feet extend well beyond routine ambulation. Specialized designs such as the Flex-Foot Cheetah and other sprinting prostheses are engineered to maximize elastic energy return, providing propulsion for running and high-impact activities. These feet lack heels and adopt a blade-like shape that optimizes speed and agility, demonstrating how performance engineering can redefine human potential in adaptive sports.

In rehabilitation contexts, prosthetic feet support the progression from initial gait training to advanced mobility tasks. Early-stage users often begin with simple, non-articulated feet for stability, later transitioning to ESR or articulated designs as strength and confidence improve. For paediatric users, lightweight and adjustable prostheses allow adaptation to growth and development, ensuring continuity of mobility.

The availability of specialized feet for sports and high-demand activities illustrates the expanding role of prosthetics not only in restoring normalcy but also in enhancing human performance. At the same time, these designs raise questions of equity and accessibility, as advanced sports prostheses are among the most expensive devices available.

AFFORDABILITY AND ACCESSIBILITY CHALLENGES

Despite remarkable advances in prosthetic foot technology, accessibility remains a persistent global challenge. For many amputees, particularly in low- and middle-income countries (LMICs), the prohibitive cost of advanced designs severely limits their adoption. Beyond affordability, issues of infrastructure, clinical expertise, and cultural compatibility further shape the availability and use of prosthetic feet.

Global Disparities in Prosthetic Foot Availability

The global distribution of prosthetic care is highly uneven. In high-income countries, amputees often have access to advanced prosthetic feet, including dynamic response and microprocessor-controlled designs, supported by insurance systems and specialized rehabilitation centres. By contrast, in LMICs, the majority of amputees rely on either no prosthesis or low-cost conventional feet due to financial constraints and limited clinical resources.

The World Health Organization estimates that fewer than 10% of people in need of assistive devices in low-resource regions actually have access to them. Barriers include the high initial cost of advanced prostheses, scarcity of trained prosthetist, limited repair and maintenance services, and lack of integration into public health systems. These disparities create a dual reality: while technological innovation continues to accelerate in wealthier regions, basic mobility needs remain unmet for millions of amputees in resource-constrained settings.

Low-Cost Innovations

Recognizing the urgent need for affordable solutions, several low-cost prosthetic feet have been developed:

The Jaipur Foot (India): A rubber-based, flexible prosthesis designed for barefoot use, squatting, and culturally relevant activities such as sitting cross-legged. It is low-cost, durable, and easily repairable making it one of the most widely distributed prosthetic feet in the developing world.

The Niagara Foot (Canada): Constructed from fiberglass and nylon composites, this foot offers higher energy return compared to traditional SACH feet while maintaining low production costs.

Table 1. Cost Performance Trade-Offs in Prosthetic Foot Development.

Design Type	Relative Cost	Performance Level	Accessibility	Notes
SACH Conventional	Very low	Low	High	Stable, basic, but poor gait restoration
Elastic Keel	Low	Moderate	High	Smooth rollover, still limited energy return
ESR Feet	High	High	Moderate (mostly in developed countries)	Efficient gait, athletic use
Microprocessor Bionic	Very high	Very high	Low (restricted to HICs)	Superior outcomes, costly and complex
Jaipur & Niagara MIT	Very low	Moderate	Very high in LMICs	Affordable, durable, culturally relevant
3D-Printed Emerging Tech	Moderate	Moderate–High	Growing	Potential balance between cost and function

MIT Low-Cost Foot (USA): Developed for LMICs, this design employs polymer composites and innovative geometry to replicate rollover dynamics similar to higher-end ESR feet, but at a fraction of the cost.

These innovations highlight how context-sensitive engineering can deliver functional, affordable mobility solutions without relying on costly materials or advanced electronics.

Trade-Offs Between Affordability and Performance

The pursuit of affordability often necessitates compromises in biomechanical sophistication, durability, and aesthetics. Conventional feet like SACH are durable and inexpensive but fail to restore efficient gait or reduce energy expenditure. Low-cost models such as the Jaipur Foot and Niagara Foot achieve functional adequacy but may not offer the same energy return, adaptability, or cosmetic appeal as advanced ESR and microprocessor feet.

On the other hand, high-performance feet deliver superior outcomes in terms of gait restoration, energy efficiency, and psychosocial benefits but are priced well beyond the reach of most amputees globally. The trade-off thus underscores a fundamental challenge: balancing engineering excellence with accessibility to ensure that innovations benefit not only a privileged minority but the global amputee population at large.

Role of 3D Printing and Emerging Technologies

Additive manufacturing, particularly 3D printing, has emerged as a promising approach to democratizing prosthetic foot production. By leveraging digital design, rapid prototyping, and locally sourced materials, 3D printing enables cost-effective customization of prosthetic feet. This reduces dependency on centralized manufacturing and allows rapid replacement or repair in remote areas.

Beyond affordability, 3D printing enhances accessibility by enabling scalable production of prostheses tailored to individual anatomy and activity needs. Community-based initiatives have already demonstrated the potential of open-source prosthetic designs, freely shared across global networks.

Emerging technologies such as bio-inspired materials, smart polymers, and artificial intelligence-driven gait adaptation also hold potential for reducing costs in the long term. For instance, modular feet with interchangeable components could extend lifespan and reduce maintenance expenses, while AI algorithms may allow simplified sensor systems to deliver performance benefits without the high costs of full microprocessor control.

COMPARATIVE ANALYSIS OF PROSTHETIC FOOT TYPES

The diversity of prosthetic foot designs reflects the need to accommodate users with varying activity levels, economic circumstances and environmental conditions. A critical comparative analysis allows clinicians, engineers, and policymakers to evaluate which designs are most appropriate for different users. The advantages and limitations of each category, their suitability based on functional classifications (K0–K4), and illustrative case studies from both developed and developing countries.

Table 2. Comparative Characteristics of Prosthetic Foot Types.

Category	Examples	Advantages	Limitations	Typical Users
Non-Articulated Feet	Convention SACH, Elastic Keel	Low cost, durable, simple design, minimal maintenance	Poor energy return, limited adaptability, asymmetric gait	Elderly, low-activity (K1) users
Articulated Feet	Single-axis, multi-axis	Improved dorsiflexion/plantarflexion, better stability on uneven terrain	Heavier, higher maintenance, shorter lifespan	Limited community ambulators (K2)
Dynamic Response ESR Feet	Seattle Foot, SAFE, Flex-Foot Cheetah, Vari-Flex	High energy return, efficient gait, reduced metabolic cost	Expensive, requires skilled fitting, limited availability in LMICs	Active community users (K3)
Microprocessor /Bionic Feet	Össur Proprio Foot, Ottobock Meridium	Real-time adaptation, smoother gait, improved balance	Very high cost, battery dependence, technical failures possible	High-activity, advanced users (K3–K4)
Low-Cost Innovations	Jaipur Foot, Niagara Foot, MIT Foot	Affordable, culturally adaptable, rugged design	Limited performance, reduced durability	LMIC populations, rural users

Advantages and Limitations of Each Category

Non-articulated feet, including conventional designs, the solid ankle cushioned heel (SACH) foot, and elastic keel models, are among the simplest prosthetic options available. Their main advantages are low cost, durability, and minimal maintenance, making them particularly suitable for elderly amputees or individuals with limited mobility needs. However, they have significant limitations, including minimal energy return, poor adaptability to uneven terrain, and a tendency to promote asymmetrical gait patterns, which may increase strain on the contralateral limb over time.

Articulated feet, such as single-axis and multi-axis designs, offer enhanced biomechanical functionality. Single-axis feet improve dorsiflexion and plantar flexion, thereby enhancing stability during stance, while multi-axis feet allow inversion and eversion, improving adaptability to varied terrain and reducing shear forces on the residual limb. Despite these benefits, articulated feet are heavier, more prone to mechanical wear, and require higher maintenance than non-articulated models. They are also costlier, which may restrict their use in low-resource settings.

Dynamic response or energy storage and return (ESR) feet represent a major advancement in prosthetic technology. These feet provide superior energy storage and release during gait, resulting in improved efficiency, reduced metabolic cost of walking, and better protection of the sound limb. They are especially beneficial for community ambulators and active users. Nonetheless, ESR feet are relatively expensive, often unavailable in low- and middle-income countries, and may show reduced effectiveness on uneven or unpredictable terrain.

Microprocessor-controlled and bionic feet offer the most advanced level of prosthetic performance. With real-time adaptive control, these feet enable smoother gait transitions, enhanced balance, and significant functional benefits for high-activity users. However, these devices are associated with very high costs, reliance on battery power, and potential susceptibility to technical failures. Consequently, their availability is largely confined to high-income settings with robust clinical infrastructure.

Finally, low-cost prosthetic feet, such as the Jaipur Foot, Niagara Foot, and MIT designs, address the pressing need for affordable and culturally adaptable solutions in resource-limited regions. Their advantages lie in affordability, local manufacturability, and adaptability to cultural practices such as barefoot walking and squatting. Despite these strengths, they lack the biomechanical sophistication of advanced prosthetic feet, demonstrate reduced durability compared to carbon-fibre composites, and often have limited aesthetic refinement.

Suitability Based on Functional Level (K0–K4 Classification

The American Orthotic and Prosthetic Association (AOPA) functional classification (K0–K4) provides a framework for prescribing prosthetic feet:

- **K0 (Non-Ambulator):** Prostheses generally not indicated, as no functional mobility is expected.
- **K1 (Household Ambulator):** Non-articulated feet (SACH, elastic keel) are appropriate, offering stability at low walking speeds and minimal functional demands.
- **K2 (Limited Community Ambulator):** Single-axis or multi-axis feet may be prescribed to improve stability on uneven terrain and facilitate limited outdoor ambulation.
- **K3 (Community Ambulator):** ESR feet are preferred, as they enable variable walking speeds, improved gait efficiency, and reduced energy expenditure.
- **K4 (High-Activity User / Athlete):** Advanced ESR or bionic feet, such as Flex-Foot Cheetah or microprocessor-controlled designs, provide high performance for running, sports, and impact-intensive activities.

Table 3. Functional Level (K0–K4) and Suitable Prosthetic Foot Types.

Functional Level	Definition	Suitable Foot Types
K0	No ability or potential to ambulate safely	Prosthesis not indicated
K1	Household ambulator, low walking speed, flat surfaces only	SACH foot, Elastic keel
K2	Limited community ambulator, uneven terrain possible	Single-axis, Multi-axis feet
K3	Community ambulator, variable speed, beyond simple locomotion	ESR feet (Seattle, SAFE, Vari-Flex)
K4	High-activity user, athlete, child, or active adult	ESR advanced, microprocessor-controlled, or bionic feet

This classification highlights the spectrum of needs: from stable and affordable designs for low-functioning amputees to advanced high-performance devices for athletes and active individuals.

Case Studies from Developed vs. Developing Countries

Developed Countries: In high-income nations such as the United States, Germany, and Japan, prosthetic users often have access to advanced ESR and microprocessor-controlled feet through insurance systems and specialized rehabilitation centre. Case studies demonstrate significant improvements in gait symmetry, energy expenditure, and quality of life for users of microprocessor feet compared to conventional designs. However, these benefits are often accompanied by high costs of acquisition, maintenance, and battery replacement.

Developing Countries: In contrast amputees in LMICs rely heavily on low-cost solutions such as the Jaipur Foot (India) and Niagara Foot (used in several African countries). These designs prioritize cultural and environmental suitability for example, barefoot walking, squatting, and agricultural work over biomechanical sophistication. Case reports from India and sub-Saharan Africa illustrate how inexpensive designs dramatically improve independence and social participation, despite lacking the performance characteristics of ESR or bionic feet.

These contrasts underscore the dual challenge in prosthetic development: while advanced designs set benchmarks for biomechanical performance, affordable and ruggedized models remain essential for meeting global rehabilitation needs. Bridging these contexts requires not only technical innovation but also policies that ensure equitable access to prosthetic technology.

Table 4. Comparative Summary of Prosthetic Foot Types: Advantages, Limitations, Functional Level.

Prosthetic Foot Type	Representative Examples	Key Advantages	Key Limitations	Typical Functional Level (K0–K4)	Remarks Clinical Suitability
Conventional Non-Articulated	SACH Foot, Wooden Foot	Very low cost, durable, simple construction,	No energy return, limited	**K1** – Household ambulator	Ideal for elderly or low-activity users;

Foot (SACH, Conventional)		minimal maintenance	adaptability to terrain, promotes asymmetrical gait		suited for resource-limited environments
Elastic Keel Foot	SAFE Foot, Elastic Keel Model	Improved rollover, some shock absorption, smoother gait than SACH	Moderate energy return, limited motion adaptability	**K1–K2**	Good transitional design for limited community ambulators
Single-Axis Articulated Foot	Endolite Multiplex, College Park Trustep	Allows controlled plantar flexion/dorsiflexion, increases knee stability	Heavy, prone to mechanical wear, requires periodic maintenance	**K2**	Suited for users requiring stability on uneven surfaces
Multi-Axis Articulated Foot	Freedom Highlander MAX, Blatchford Multi flex	Adapts to uneven terrain (inversion/eversion), enhances comfort and balance	Increased weight and cost, reduced durability	**K2–K3**	Recommended for active users navigating outdoor environments
Dynamic Response Energy Storage and Return (ESR) Foot	Seattle Foot, Vari-Flex, Flex-Foot, Ossur Cheetah	High energy return, efficient gait, reduced metabolic cost, improved symmetry	High cost, requires skilled alignment, limited accessibility in LMICs	**K3–K4**	Gold standard for community and athletic users; enhances dynamic performance
Microprocessor-Controlled & Bionic Foot	Össur Proprio Foot, Ottobock Meridium, Blatchford Elan	Real-time adaptation, automatic terrain response, enhanced stability and balance	Very high cost, battery dependence, maintenance complexity	**K3–K4**	Premium prosthesis for advanced users; primarily available in high-income regions
Low-Cost Culturally Adaptive Foot	Jaipur Foot, Niagara Foot, MIT Low-Cost Foot	Extremely affordable, locally Manufacturable, culturally compatible (barefoot walking,	Limited biomechanical performance, aesthetic limitations,	**K1–K2**	High social impact; ideal for low-resource and rural contexts

		squatting)	moderate durability		
3D-Printed or Modular Foot (Emerging Technology)	Open Bionics 3D Foot, e-NABLE Models	Customizable, lightweight, repairable, cost-effective production	Emerging technology, limited clinical validation, variable durability	**K2–K3**	Promising option for scalable, affordable prosthetic production and personalization

FUTURE PERSPECTIVES IN PROSTHETIC FOOT DEVELOPMENT

The trajectory of prosthetic foot design demonstrates remarkable progress, from rigid wooden blocks to advanced bionic systems. Yet, challenges of cost, accessibility, and sustainability remain unresolved. Future research and development must therefore not only push technological boundaries but also ensure inclusivity and equity. Emerging trends in robotics, artificial intelligence, personalized medicine, and sustainable engineering are expected to shape the next generation of prosthetic feet.

Advances in Robotics Sensor Integration

The incorporation of robotics and artificial intelligence is transforming prosthetic foot functionality. Modern prototypes integrate multi-sensor arrays including accelerometers, gyroscopes, and pressure sensors that continuously monitor gait parameters and environmental conditions. These data are processed by embedded algorithms to adapt resistance, ankle angle, and energy return in real time, thereby mimicking the responsiveness of the biological foot.

Robotics further enables powered propulsion, offering active push-off during gait rather than passive energy return. Such designs are particularly valuable for individuals with higher functional demands (K3–K4 users) and for tasks requiring adaptability across terrains. Advances in machine learning may soon allow prosthetic feet to "learn" user-specific gait patterns, enhancing personalization and reducing rehabilitation time.

Personalized and Adaptive Prosthetic Solutions

Personalization is emerging as a cornerstone of prosthetic design. Future systems are expected to incorporate **adaptive control mechanisms** that respond to individual gait patterns, residual limb characteristics, and activity levels. Adjustable stiffness, customizable energy return, and modular design features may allow a single prosthetic foot to adapt dynamically across contexts from walking and climbing stairs to running or squatting.

3D scanning and computer-aided design (CAD) already enable anatomically tailored prosthetic components. When coupled with advanced materials and additive manufacturing, these tools will support scalable customization, reducing production costs and enhancing user satisfaction. Personalized prostheses could also be integrated with wearable health technologies, such as pressure mapping systems, to provide real-time feedback on fit and performance.

Sustainability and Eco-Friendly Prosthetic Designs

Sustainability is an increasingly important priority in biomedical engineering. Conventional prosthetic feet rely heavily on carbon fiber and polymers, which are costly and environmentally burdensome to produce. Emerging research is exploring eco-friendly alternatives, such as biodegradable polymers, natural fiber, and recycled composites.

Sustainable design also extends to product lifecycle management. Modular feet with replaceable components can extend usability, reducing waste and lowering long-term costs. In LMICs, locally sourced materials combined with simplified manufacturing processes could provide durable yet environmentally responsible solutions. By prioritizing sustainability, future prosthetic development can simultaneously address ecological and socioeconomic concerns.

Path toward Universally Accessible Prosthetic Technology

Perhaps the greatest challenge lies in ensuring that innovations reach all amputees, not just those in high-income countries. Universal accessibility requires a multi-pronged strategy:

Policy and funding mechanisms that support prosthetic provision in public health systems.

Low-cost innovations that retain sufficient performance to meet the mobility needs of LMIC populations.

Global collaborations between engineers, clinicians, governments and non-governmental organizations to promote technology transfer and capacity building.

Open-source designs that allow local adaptation and manufacturing of affordable prosthetic feet using widely available materials and techniques.

A sustainable path forward involves integrating high-tech and low-cost solutions into a unified framework: advanced designs will continue to evolve for athletes and high-demand users, while simplified, durable versions ensure basic mobility for the global majority. The ultimate goal is to create prosthetic foot technology that is not only biomechanically advanced but also universally accessible, affordable, and culturally appropriate.

CONCLUSION

This review highlights the evolution of prosthetic foot technology from basic non-articulated designs, such as the SACH foot, to advanced energy storage, microprocessor-controlled, and bionic models. Each category offers distinct biomechanical, therapeutic, and psychosocial benefits, yet limitations in cost, adaptability, and accessibility remain. Evidence consistently demonstrates that prosthetic feet significantly improve gait restoration, reduce energy expenditure, and enhance quality of life. However, disparities persist: while high-performance devices are available in developed contexts, millions of amputees in low- and middle-income countries continue to rely on low-cost alternatives that often sacrifice biomechanical efficiency for affordability. The path forward requires balancing innovation, cost and accessibility. Advances in robotics, artificial intelligence, and sustainable materials show promise for bridging this divide, but their translation into universally affordable solutions remains limited. Research gaps exist in long-term clinical outcomes, durability in diverse environments and integration of emerging technologies into scalable, low-cost designs. Future studies should prioritize interdisciplinary collaboration uniting engineers, clinicians, policymakers, and manufacturers to develop prosthetic feet that are not only technologically sophisticated but also economically and culturally accessible. Achieving this balance will ensure that the benefits of modern prosthetic development reach the global amputee population equitably.

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