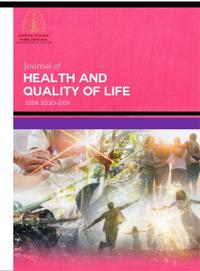




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Review on the Biomechanics and Functional Performance of Lower-Limb Prosthetic Devices

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ABSTRACT

Lower limb prostheses play a crucial role in restoring mobility, balance, and quality of life for individuals with lower limb amputations. Practical prosthetic function depends on how well artificial joints replicate the biomechanical roles of natural human joints, particularly the ankle, knee, and hip, during gait. This review synthesises biomechanical principles and recent technological advances in prosthetic limb design, with a particular emphasis on prosthetic knees and ankle-foot systems. Natural joints play a crucial role in walking by supporting body weight, absorbing shock, storing and returning energy, and facilitating smooth limb trajectories during both the stance and swing phases. Replicating these functions in prosthetic devices remains challenging due to limitations in force distribution, energy management, adaptability, and user device integration. Current prosthetic solutions range from passive systems, such as energy storage and return (ESAR) feet and mechanical knees, to quasi-passive microprocessor-controlled devices and fully powered prostheses. Passive designs offer simplicity and reliability, but they are limited in terms of adaptability and energy return. Microprocessor-controlled knees enhance stability, gait symmetry, and safety by adjusting damping in real-time. At the same time, powered prostheses can deliver net positive work, enabling more natural propulsion and improved performance on stairs and slopes. However, these advanced systems introduce trade-offs in terms of weight, power consumption, and complexity. A critical factor influencing comfort and performance is force distribution at the socket-residual limb interface, where poor load transfer can lead to pain, tissue damage, and altered gait patterns. Despite significant progress, challenges remain in achieving consistent energy efficiency, robust terrain adaptability, and intuitive control. Continued multidisciplinary research in materials, sensing, control algorithms, and clinical socket design is crucial to narrowing the gap between artificial and biological limb biomechanics and enhancing real-world functional outcomes for prosthetic users.

1. Introduction

Globally, approximately 38 million people live with major amputations, with around 85% of these cases involving the loss of a lower limb [1]. The impact of lower-limb amputation extends beyond mobility limitations, affecting independence, social participation, and overall quality of life. Prosthetic technology has therefore become a cornerstone in rehabilitative care, enabling amputees

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to regain functional mobility and engage in daily activities with confidence. Among biomedical engineering disciplines, the study of prosthetic limb movement has gained increasing attention due to its potential to restore or even enhance natural limb function. The primary objective of prosthetic design is to replicate the biomechanical and neuromuscular characteristics of human joints, allowing artificial limbs to move in coordination with the user's body.

Lower-limb amputees rely heavily on prosthetic knees, ankles, and hips to perform essential activities such as walking, running, climbing stairs, and maintaining postural balance. These joints must not only support the body's weight but also dynamically respond to varying terrains, forces, and movement speeds, all while ensuring user comfort and safety [2]. Achieving a natural gait in prosthetic users remains a complex challenge due to the inherent differences between biological limbs and mechanical systems. Human joints operate through intricate interactions among muscles, tendons, and neural feedback, efficiently controlling energy transfer, force generation, and motion patterns in ways that are difficult to replicate artificially [3].

Recent advancements in prosthetic technology have focused on bridging this gap through innovations such as microprocessor-controlled joints, powered actuators, adaptive ankle-foot systems, and bio-inspired designs that mimic muscle-tendon mechanics. These approaches aim to improve energy efficiency, enhance stability, and produce more fluid, human-like movement. Additionally, integrating sensors and machine-learning algorithms allows prosthetic devices to anticipate and adapt to user intent and environmental conditions, further approaching natural limb function. Despite these technological improvements, challenges remain in creating prosthetic joints that can fully replicate the versatility, responsiveness, and energy economy of biological limbs [4].

This review provides a comprehensive analysis of current prosthetic joint technologies, examining their strategies for mimicking natural motion, the biomechanical and energetic challenges they encounter, and emerging innovations aimed at achieving more seamless, adaptive, and functional limb replacement solutions. By understanding both the limitations and advancements in prosthetic design, researchers and clinicians can better guide the development of next-generation devices that enhance mobility, independence, and quality of life for individuals with lower-limb amputations.

Lower-limb prostheses play a crucial role in restoring mobility, independence, and overall quality of life for individuals living with amputation. Beyond merely replacing the missing limb, modern prosthetic devices are designed to replicate the complex mechanical functions of the hip, knee, and ankle during locomotion. Successful prosthetic function requires the joint to fulfil several key roles throughout the gait cycle. During the stance phase, prosthetic joints must support body weight, maintain postural stability, and safely transfer forces through the limb. Simultaneously, they must absorb and store energy generated during ground contact, then return it efficiently to aid propulsion during the swing phase. Additionally, they must control the limb's trajectory and orientation to prevent trips or falls, ensuring a smooth, energy-efficient gait that closely mimics natural motion. Achieving these functions in a mechanical system poses significant biomechanical and engineering challenges due to the complex interactions among muscles, tendons, and neural feedback in biological limbs [5].

Historically, lower-limb prosthetic design focused on passive systems that prioritised durability and basic mobility. Early prosthetic feet and knees relied on simple, rigid or articulated mechanisms that provided limited energy storage and minimal adaptability to changing terrain. Over the last two decades, there has been a dramatic evolution toward more sophisticated designs. Energy-storing and energy-returning (ESAR) prosthetic feet were introduced, utilising elastic materials and spring mechanisms to store kinetic energy during stance and release it to assist propulsion, improving walking efficiency and reducing metabolic cost. The introduction of microprocessor-controlled knees (MPKs) marked a paradigm shift, allowing real-time adjustment of joint resistance, swing speed, and

stance stability based on sensor input. Powered ankle–foot systems and powered prosthetic knees further extended this capability by actively generating torque, rather than merely controlling passive motion, enabling smoother transitions and more natural gait patterns, particularly during uphill walking, stair ascent, or running.

Despite these advances, fundamental biomechanical challenges persist. Force distribution across prosthetic joints remains a key concern, as improper loading can lead to residual limb pain, skin breakdown, or musculoskeletal complications in the hip and spine. Energy management in powered devices is still limited by battery life and actuator efficiency, and replicating the adaptive responsiveness of human neuromuscular control remains difficult. Additionally, current prostheses often struggle to match the versatility and coordination of biological limbs, especially at variable walking speeds, on irregular terrain, or during dynamic activities [6].

This review aims to provide a comprehensive overview of biomechanical principles underlying hip, knee, and ankle prostheses, highlighting how contemporary designs attempt to replicate natural joint mechanics. By examining current solutions and persistent limitations, this review also identifies areas for future research, including improvements in force distribution, energy efficiency, control strategies, and user-specific customisation, all of which are essential for closing the remaining gap between prosthetic and biological joint function.

Human joints are remarkable structures, providing a unique combination of strength, flexibility, and energy efficiency that enables complex, coordinated movement. Among these, the ankle joint plays a pivotal role in locomotion by linking the foot to the lower leg and facilitating precise control of the body's interactions with the ground. The ankle is a highly mobile hinge joint that allows multiple planes of motion, enabling the foot to adjust to varying terrain and absorb impact forces during walking, running, or jumping. Key movements at the ankle include plantar flexion (PF), in which the foot points downward, and dorsiflexion (DF), in which the foot lifts upward along the sagittal plane [7]. In addition, the ankle permits adduction and abduction, which move the foot medially and laterally, respectively, allowing subtle side-to-side adjustments necessary for balance and stability. These motions are coordinated through the complex interplay of bones, ligaments, tendons, and muscles, particularly the gastrocnemius, soleus, and tibialis anterior, which modulate force and absorb energy during each step.

The ankle's capacity to store and return elastic energy, particularly through the Achilles tendon, contributes significantly to the efficiency of walking and running. During the stance phase of gait, energy is absorbed as the foot contacts the ground, while during push-off, this energy is released to propel the body forward. Such mechanisms reduce metabolic cost and ensure a smooth, stable gait cycle [8]. The precise coordination of ankle movements with the knee and hip is essential for maintaining balance, controlling stride length, and adapting to environmental changes. Consequently, replicating ankle function remains one of the most challenging aspects of lower-limb prosthetic design, as artificial systems must reproduce not only the mechanical range of motion but also the energy storage and dynamic responsiveness characteristic of biological joints.

1.1 Prosthetic Knees: Design, Function, and Technological Advancements

The human knee joint is a complex hinge that provides stability, supports body weight, and enables locomotion through controlled flexion and extension. Prosthetic knees are engineered to replicate these essential functions, allowing individuals with lower-limb amputations to walk safely, maintain balance, and perform daily activities. The primary goal of prosthetic knee design is to facilitate a smooth and coordinated gait cycle, ensuring safe transitions between the stance phase,

when the limb supports weight, and the swing phase, when the leg moves forward to complete a step [8]. Achieving this requires careful attention to both mechanical stability and energy efficiency.

Prosthetic knees are generally classified into three main types [9]:

1. Passive knees, which rely on purely mechanical systems such as springs, friction brakes, or dampers to control motion. These devices provide basic functionality, enabling flexion and extension without the need for active control systems. While durable and lightweight, passive knees are limited in their adaptability to varying walking speeds or complex terrains.
2. Semi-active knees, which incorporate adjustable resistance mechanisms using hydraulics, pneumatics, or magnetorheological fluids. These systems allow the knee to modulate resistance in response to user movement, providing improved stability and smoother transitions compared to purely passive devices. Semi-active knees are particularly useful in uneven terrain and variable gait speeds, as they can dynamically adjust damping to reduce the risk of falls.
3. Active or powered knees, which utilise sensors, microprocessors, and actuators to assist joint motion actively. These advanced prostheses can generate torque at the knee, mimic the natural biomechanics of gait, and adapt in real time to changes in walking speed, slope, or activity type. Powered knees represent the most sophisticated approach to prosthetic design, offering enhanced mobility and more natural gait patterns, though they often come with increased weight, cost, and power requirements.

Modern prosthetic knees are constructed from high-performance materials such as titanium, aluminium alloys, and carbon fibre composites, providing a balance between strength, durability, and lightweight performance. The integration of microprocessors and embedded sensors allows these devices to monitor limb orientation, detect gait phases, and adjust joint resistance or power output accordingly. This technological integration not only improves gait symmetry and energy efficiency but also reduces compensatory movements and strain on other joints, such as the hip and lower back, which are common issues among amputees [10].

Despite these advancements, replicating the full functionality of the human knee remains a challenge. Prosthetic knees must manage variable loading, maintain stability under sudden perturbations, and coordinate seamlessly with the ankle and hip joints to ensure efficient, safe, and fatigue-free walking. Consequently, research continues to focus on enhancing control algorithms, actuator efficiency, energy regeneration, and user-specific customisation further to narrow the gap between prosthetic and biological knee performance.

1.2 Force Distribution and Biomechanical Considerations in Prosthetic Knees

Force distribution is a critical aspect of lower-limb biomechanics, referring to how body weight and impact forces are absorbed and transmitted through the joints during activities such as walking, running, or stair negotiation [11]. In a natural leg, the knee, along with surrounding muscles and ligaments, functions as a dynamic shock absorber, distributing forces evenly across the joint and minimising stress on the bones and soft tissues. Muscles such as the quadriceps, hamstrings, and gastrocnemius work synergistically to control joint loading, stabilise the limb, and provide energy-efficient movement.

For individuals using prosthetic limbs, the artificial joint must assume this role in the absence of natural muscle control. Improper force distribution can lead to a range of complications, including residual limb pain, skin irritation, gait instability, and overuse injuries in the intact limb or proximal joints such as the hip and lower back. This highlights the importance of careful prosthetic alignment, structural design, and appropriate selection of knee type to mimic natural load transfer as closely as possible.

Modern microprocessor-controlled knees (MPKs) have been developed to address these challenges by actively regulating resistance and joint motion to produce more natural gait patterns. Devices such as the C-Leg, Rheo Knee, and Power Knee use embedded sensors to detect user motion and adjust hydraulic or motorised resistance during stance and swing phases. Research has shown that these knees generate different joint work patterns depending on the activity, terrain, or slope, such as during ramp ascent or descent and stair negotiation [12]. By modulating joint stiffness and energy absorption, MPKs can reduce excessive stress on the residual limb and compensate for the lack of muscular control, ultimately improving gait symmetry and comfort.

Despite these technological advances, achieving optimal force distribution remains a significant challenge. Individual variations in residual limb length, muscle strength, and walking habits mean that prosthetic alignment and tuning must often be personalised. Future developments may focus on adaptive control algorithms, real-time feedback systems, and integration with powered ankle-foot systems, aiming to more closely replicate the dynamic force management of biological joints and reduce long-term musculoskeletal complications for prosthetic users.

1.3 Energy Storage and Return in Prosthetic Knees

In the biological leg, muscles and tendons play a critical role in energy management during walking. As the knee bends during the stance phase, elastic structures such as the quadriceps tendon and patellar tendon store mechanical energy, which is then released during knee extension to help propel the body forward. This natural energy recycling contributes significantly to walking efficiency, reducing the metabolic cost of locomotion. In addition to the knee, coordinated action of the hip and ankle further optimises energy use by storing and returning energy through tendons and elastic tissues.

Prosthetic knees aim to replicate this energy storage and return (ESAR) mechanism using mechanical, semi-active, or powered systems [13]. Passive knees typically rely on springs or dampers to control motion. While they can absorb energy during flexion, they generally return only a small fraction of it, which can make walking more physically demanding for the user. In contrast, semi-active and powered knees incorporate hydraulics, pneumatics, or motorised actuators to allow controlled storage and release of energy. These systems can, for example, use spring-loaded mechanisms or active torque generation to recover some of the energy lost at each step, reducing fatigue and improving gait efficiency.

Despite these advancements, matching the timing, magnitude, and smoothness of energy return to that of human muscles remains a significant challenge. The dynamic coordination of multiple joints and muscles in a natural leg is complex to replicate mechanically, leading to residual energy loss. Consequently, amputees using prosthetic knees often expend more metabolic energy and experience greater physical effort than non-disabled individuals during walking, particularly at faster speeds or on uneven terrain [14]. Ongoing research focuses on improving actuator responsiveness, energy regeneration, and real-time control algorithms to better synchronise energy return with user movement, ultimately aiming to narrow the efficiency gap between prosthetic and biological knees.

1.4 Efficiency and Control

Efficiency in prosthetic knees refers to the device's ability to utilise energy effectively to support natural, stable, and fatigue-free movement. A highly efficient prosthetic knee minimises the physical effort required by the user, enabling smoother gait transitions and reducing compensatory movements that could strain other joints or the lower back [15]. Achieving this level of efficiency depends not only on mechanical design but also on the integration of advanced control systems. Modern powered prosthetic knees leverage sensors, microprocessors, and actuators to regulate joint motion and resistance in real time actively. These intelligent control systems monitor parameters such as knee angle, angular velocity, and ground reaction forces to adapt the prosthetic response to walking speed, terrain, and activity type. For example, during ramp ascent or stair climbing, powered knees can provide additional torque to assist knee extension, reducing user effort and improving gait symmetry. Similarly, during descent, controlled resistance can enhance stability and prevent falls.

Despite these advantages, achieving optimal efficiency remains challenging. Powered systems must balance energy consumption, device weight, and reliability, as excessive power demands or heavy components can compromise user comfort and mobility. Additionally, control algorithms must respond rapidly to gait variations without introducing delays or instability, which requires sophisticated sensor integration and real-time processing. Ongoing research in prosthetic knee design focuses on improving energy efficiency through regenerative actuators, adaptive control strategies, and lightweight materials, with the ultimate goal of narrowing the functional gap between prosthetic and biological knees and providing amputees with mobility that closely resembles natural walking.

1.5 Challenges and Innovations in Prosthetic Knees

Despite substantial advances in prosthetic knee technology, several biomechanical and engineering challenges remain that limit these devices' ability to replicate natural knee function [16] fully. One major issue is uneven force distribution, which can result from improper loading of the residual limb or misalignment of the prosthesis and cause discomfort, skin breakdown, or musculoskeletal injuries in the hip and lower back. Another persistent limitation is insufficient energy return. While semi-active and powered knees can store and release energy, they cannot match the timing and efficiency of biological muscle-tendon systems, resulting in a higher metabolic cost and greater effort for amputees.

The weight and complexity of advanced prosthetic knees also pose practical challenges. Powered systems require batteries, actuators, and electronic control units, which can increase device mass and reduce user comfort or mobility. Additionally, prosthetic knees must adapt seamlessly to changing terrains, including stairs, slopes, and uneven ground, which requires rapid sensing, real-time control adjustments, and highly responsive actuation. Failure to achieve this can compromise gait stability and increase fall risk.

To address these challenges, current research is exploring several innovative approaches. Lightweight, high-strength materials, such as carbon fibre composites and titanium alloys, reduce overall device weight without compromising durability. Advanced control algorithms, including those based on artificial intelligence and machine learning, enable microprocessor-controlled knees to predict user intent and dynamically adjust resistance or power output. Furthermore, energy-regenerative systems are being developed to capture and recycle kinetic energy during walking, storing it for subsequent push-off or swing-phase assistance, thereby improving energy efficiency.

The overarching goal of these innovations is to create prosthetic knees that not only restore mobility but also replicate the biomechanical performance, responsiveness, and comfort of natural human knees. By improving force distribution, energy return, adaptability, and control efficiency, these next-generation devices aim to allow users to walk naturally across diverse terrains with reduced effort, enhanced stability, and greater confidence in daily life.

2. Biomechanical Roles of the Natural Lower-Limb Joints

Understanding the biomechanical functions of natural lower-limb joints is essential for guiding the design of prosthetic components that replicate normal gait. Each joint contributes uniquely to locomotion, providing stability, energy efficiency, and smooth forward progression [17].

- **Ankle–Foot Complex:** The ankle and foot work together to control motion during walking. At heel strike, the ankle undergoes controlled plantarflexion to allow a smooth foot contact with the ground. During mid-stance, elastic structures such as the Achilles tendon store energy, which is subsequently returned in terminal stance and pre-swing to assist propulsion. This energy storage and return reduces metabolic cost, smooths forward progression, and improves overall gait efficiency. The foot’s multi-directional mobility also enables adaptability to uneven surfaces and balance control.
- **Knee:** The knee serves several critical functions during locomotion. It provides stance stability by resisting collapse under body weight, absorbs shock through controlled early-stance flexion, and allows rapid flexion and extension during the swing phase for foot clearance. The knee’s ability to manage forces and coordinate with the ankle and hip is vital for maintaining an energy-efficient and safe gait.
- **Hip:** The hip is the primary generator of mechanical power for forward progression, particularly during push-off and when walking on inclines. It also controls limb swing and contributes to trunk stability, ensuring coordinated and balanced motion. Hip mechanics are essential for maintaining stride length, adapting to terrain changes, and compensating for variations in ankle and knee function.

Collectively, these biomechanical roles define design targets for prosthetic joints, including appropriate stiffness, damping characteristics, active power generation, and joint alignment. By replicating these functions, prosthetic devices can improve walking efficiency, stability, and overall mobility for amputees.

2.1 Replication of Natural Movement in Prosthetic Joints

Prosthetic joints aim to replicate the complex biomechanical functions of biological limbs by restoring stability, propulsion, and energy efficiency. Current prosthetic designs achieve this through three broad strategies: passive (mechanical), quasi-passive (adaptive/damped), and active (powered). Each approach offers distinct advantages and limitations in terms of adaptability, energy return, and gait naturalness [18].

1. Passive Prostheses

Passive prosthetic solutions rely solely on mechanical elements to control motion. Energy-Storing-and-Return (ESAR) feet use compliant carbon-fibre structures to store elastic energy during

mid-stance and release it during late stance, partially substituting for the energy typically provided by muscles and tendons. Compared with rigid designs such as Solid Ankle Cushioned Heel (SACH) feet, ESAR devices improve gait symmetry and reduce metabolic cost. However, their energy return is limited and non-adaptive to changes in terrain or walking speed.

Passive mechanical knees incorporate springs, hydraulic dampers, polycentric linkages, or locking mechanisms to provide stance stability and swing control. Their primary advantages are simplicity, reliability, and low maintenance, making them durable and predictable for daily use. However, they lack adaptability, resulting in less efficient gait transitions when walking at varying speeds, negotiating stairs, or navigating slopes.

2. Quasi-Passive and Microprocessor-Controlled Prostheses

Quasi-passive devices, particularly microprocessor-controlled knees (MPKs), introduce real-time adaptability by modulating resistance during stance and swing phases. MPKs integrate sensors and algorithms to adjust hydraulic or pneumatic damping according to the user's motion, improving stability, gait symmetry, and safety. These systems have been shown to reduce fall risk and increase community mobility compared with purely mechanical knees. Similarly, quasi-passive ankles and feet incorporate adaptive elements, such as variable stiffness mechanisms or clutches, enabling partial adjustment to terrain and load, thereby improving comfort and functional performance relative to fixed passive designs.

3. Active (Powered) Prostheses

Active prosthetic joints employ motors or actuators, combined with sensors and real-time control systems, to deliver net positive work, actively assisting propulsion and replicating the power output of muscles. Powered knees and ankles allow users to walk at variable speeds, ascend stairs, and negotiate slopes in a manner closer to able-bodied biomechanics. Recent control strategies, such as intent recognition, finite-state controllers, and model-based approaches, have further enhanced coordination between the prosthesis and the user's residual limb, allowing smoother transitions between gait phases and reducing compensatory demands on proximal joints, such as the hip or lower back.

While active prostheses offer the most significant potential to replicate natural movement, challenges remain. Increased weight, power consumption, and mechanical complexity can affect user comfort, battery life, and long-term reliability. Nevertheless, studies demonstrate that powered devices can normalise joint power profiles, improve energy efficiency, and reduce physical effort compared with passive or quasi-passive alternatives, highlighting their promise in approaching actual biomimetic locomotion.

3. Socket–Residual Limb Interface: Importance and Challenges

The interface between the prosthetic socket and the residual limb is a critical determinant of comfort, function, and long-term prosthesis use. The socket must effectively transfer ground reaction forces and joint moments from the prosthesis to the residual skeletal structures and surrounding soft tissues while minimising pain, pressure sores, and tissue damage. Achieving a physiologically appropriate distribution of pressure and shear forces is particularly challenging due to several factors, including variations in residual-limb shape, soft-tissue compliance, and dynamic loading during gait.

Residual-limb volume and shape can fluctuate throughout the day due to swelling, muscle contraction, or weight changes, altering the fit and pressure distribution within the socket. Additionally, the mechanical properties of soft tissues differ across individuals and regions, making uniform force transfer difficult. Inadequate force distribution can lead to discomfort, skin breakdown, altered gait patterns, and even long-term musculoskeletal complications, contributing to prosthesis dissatisfaction or abandonment [19].

To address these challenges, research has focused on adjustable, modular socket designs that allow customisation and fine-tuning of fit over time. Advanced measurement techniques, including interface pressure sensors, infrared imaging, and computational modelling, are being used to map pressure distributions and optimise socket geometry. These innovations aim to reduce pressure points, improve load transfer, and enhance overall comfort, ultimately supporting safer, more efficient gait mechanics. Properly designed and fitted sockets not only protect tissue integrity but also facilitate more natural movement and energy-efficient walking, highlighting their central role in successful prosthetic rehabilitation.

3.1 Energy Storage, Return Efficiency, and Metabolic Implications in Prosthetic Feet

A key function of the ankle-foot complex in natural locomotion is storing and returning elastic energy, thereby reducing muscular effort and enhancing gait efficiency. Prosthetic feet, particularly carbon-composite Energy-Storing-and-Return (ESAR) designs, aim to replicate this function by using compliant materials that deform under load and release energy during late stance. These devices can significantly improve terminal-stance power, assisting forward propulsion and partially substituting for the work usually generated by the ankle plantarflexors. Consequently, ESAR feet can reduce muscular demand on the residual limb and improve gait symmetry compared with rigid designs, such as SACH feet.

However, the energy return of passive ESAR devices is limited. It is highly dependent on walking speed, direction, and load, and passive structures cannot generate net positive work. This limitation becomes especially evident in activities that require additional power, such as ascending slopes, climbing stairs, or walking at variable speeds. In contrast, powered prosthetic ankles can actively generate positive work, delivering propulsion in synchrony with the user's gait. These systems can improve functional performance on demanding tasks and more closely replicate the biomechanical work profiles of able-bodied ankles [20].

The metabolic implications of these technologies are an essential consideration. Passive ESAR feet often reduce muscle activity in the residual limb but do not consistently translate into significant metabolic savings, especially during complex or prolonged tasks. Powered devices, when used actively, can reduce physiological effort during challenging locomotor activities. Yet, these benefits come with trade-offs, including increased device mass, energy consumption, and control system complexity. Comparisons across prosthetic types, walking conditions, and user populations remain an active area of research, with ongoing efforts to quantify the relationships among energy storage capacity, return efficiency, and metabolic cost.

3.2 Sensing and Control for Replicating Natural Movement

Accurately replicating natural joint movement in prosthetic devices requires integrating sensing technologies and advanced control algorithms. Modern prosthetic joints use sensors such as inertial measurement units (IMUs), load cells, and joint encoders to monitor limb orientation, angular velocity, ground reaction forces, and interactions with the residual limb in real time. These data

provide essential information about the user's gait phase, walking speed, terrain, and movement intentions, forming the basis for adaptive prosthetic responses.

Control strategies translate sensor inputs into mechanical actions to replicate the timing, magnitude, and direction of forces produced by natural joints. Traditional approaches include finite-state machines, which divide the gait cycle into discrete phases with predefined control outputs, and impedance control, which modulates joint stiffness and damping to emulate biological joint dynamics. More recently, machine-learning-based intent recognition has emerged, enabling prostheses to predict user intentions from sensor patterns and adjust behaviour dynamically, allowing smoother transitions across activities such as walking, stair negotiation, and slope ascent.

Despite these advances, achieving robust, real-time control across variable terrains and activities remains a significant challenge. Systems must respond rapidly and accurately to changes in gait without introducing delays or instability, all while maintaining low computational load and energy consumption to ensure practical daily use. Ongoing research focuses on improving sensor fusion, adaptive algorithms, and predictive control to allow prosthetic devices to replicate natural movement with greater fidelity, reliability, and energy efficiency, ultimately reducing user effort and enhancing functional mobility [21].

3.3 Key Challenges in Prosthetic Joint Design

Despite significant technological advancements, several interrelated challenges continue to limit prosthetic joints' ability to replicate natural limb function fully. These challenges span biomechanics, materials, control systems, and user-device integration, and they collectively influence gait quality, comfort, and long-term prosthesis use. Force Distribution and Socket Fit: Consistent load transfer from the prosthesis to the residual limb remains difficult due to fluctuations in residual limb volume and the heterogeneous mechanical properties of soft tissues. Variations in soft-tissue compliance and bone prominence can create high-pressure areas, leading to discomfort, skin breakdown, and impaired gait. Research into adjustable sockets, modular interfaces, and novel cushioning or compliant materials aims to optimise pressure distribution and improve both comfort and function. Accurate socket design and alignment are essential not only for mechanical stability but also for long-term musculoskeletal health.

- **Energy Efficiency Versus Weight and Autonomy:** While powered prostheses can restore positive mechanical work and improve gait efficiency, they rely on onboard batteries and actuators, creating trade-offs between energy delivery, device mass, and operational autonomy. Increasing energy density, improving actuator efficiency, and minimising component weight are critical design goals. The balance between performance and portability remains a persistent engineering challenge, as heavier devices can increase metabolic cost and reduce user compliance.
- **Terrain Adaptability and Stability:** Replicating the human limb's rapid, robust adaptation to uneven terrain, stairs, slopes, and slips remains a significant challenge. While microprocessor-controlled knees (MPKs) and powered ankle-foot systems offer improved responsiveness and stability, they are not yet universally reliable under all environmental conditions. Delays in sensing or actuation, limitations in control algorithms, and variability in user movement patterns can increase fall risk and reduce confidence in daily mobility.

- **User–Device Integration:** The overall success of a prosthetic system depends not only on joint mechanics but also on the integration of socket, interface materials, alignment, and control systems. Comfort, intuitive control, and long-term tissue health are heavily influenced by this holistic design. Clinical outcomes vary widely among users, highlighting the need for personalised prosthetic fitting, adaptive interfaces, and training to maximise function and prevent secondary complications such as overuse injuries in the intact limb [22].

Addressing these challenges requires a multidisciplinary approach that combines advances in materials science, biomechanics, sensor technologies, control algorithms, and clinical practice. Emerging research in lightweight, adaptive structures, energy-regenerative actuators, and intelligent control systems aims to improve comfort, efficiency, and reliability, ultimately narrowing the gap between prosthetic and biological joint performance.

4. Conclusions

The biomechanics of prosthetic knees and lower-limb joints represent a critical intersection of engineering, human physiology, and rehabilitation, aiming to restore mobility, independence, and quality of life for amputees. Modern prosthetic joints have achieved substantial progress: ESAR feet and advanced mechanical knees replicate aspects of elastic function and stability; microprocessor-controlled and quasi-passive devices adapt damping to the user's gait phase; and powered prostheses can deliver net positive work to assist propulsion. These innovations have improved comfort, balance, and functional performance, bringing prosthetic movement closer to that of natural limbs. Despite these advances, fully reproducing the integrated, adaptive, and energetically efficient behaviour of biological lower limbs remains an ongoing challenge. Key limitations include reliable force distribution at the socket interface, efficient energy storage and generation without excessive device mass, and robust, low-latency control systems that generalise across varied terrains, speeds, and individual users. Overcoming these bottlenecks requires multidisciplinary progress in materials science, sensing technologies, control algorithms, and clinical socket design. Future prosthetic joints are expected to become increasingly intelligent, energy-efficient, and responsive, providing more natural and adaptable gait patterns. Continued research and clinical trials that link laboratory biomechanics to real-world function and patient-reported outcomes will be essential in guiding innovations that translate into meaningful improvements in mobility, safety, and quality of life for prosthetic users.

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