Enhancing Energy Efficiency using Lower Limb Prostheses: A Literature Review

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Abstract

Introduction: Lower limb prostheses by advancements in materials, design, and technology aimed at restoring mobility and decreasing energy consumption for individuals with amputations have evolved significantly over the past few decades. This study aims to review articles investigating the energy consumption of lower limb prostheses, focusing on design characteristics, material properties, and user-specific factors influence energy efficiency and functional performance. **Materials and Methods:** This literature review study reviewed design characteristics, material properties, and user-specific factors of lower limb prostheses by employing a comprehensive search strategy across multiple electronic databases, including PubMed, Web of Science, and Scopus, to identify relevant studies published up to November 2024. The search strategy was structured using the PICO framework, utilizing keywords such as "lower limb prostheses," "energy consumption," "design characteristics," "material properties," and "user-specific variables" to ensure a thorough exploration of the literature. **Results:** This literature review analyzes 10 articles on lower limb prosthetics and their impact on energy consumption of its users. Key findings revealed that advancements in materials, such as carbon fiber and smart technologies, significantly enhance energy efficiency, reduce fatigue, and improve user mobility. Furthermore, the integration of personalized fitting and rehabilitation strategies plays a crucial role in optimizing outcomes for users. **Conclusion:** The review underscores the importance of personalized fitting and rehabilitation strategies in enhancing the functionality and quality of life for amputees. By focusing on user-centered design and technological advancements, the findings highlight the potential for energy-efficient prosthetic devices to improve mobility and reduce healthcare costs, ultimately facilitating greater independence for users.

Keywords: Energy Metabolism; Lower Limb Prostheses; Rehabilitation; Smart Technology; Material Science Innovations

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Introduction

The development of lower limb prostheses has undergone remarkable transformation over the past few decades, driven by innovations in materials, design, and technology. These advancements are not only aimed at restoring mobility for individuals with amputations but also at enhancing their overall quality of life (1). Efficient ambulation is important for amputees, as it significantly impacts their energy expenditure during daily activities, making the study of energy-efficient prosthetic designs crucial for improving rehabilitation outcomes (2).

Traditional prosthetic limbs often require more energy to operate than biological limbs, leading to increased fatigue and reduced functional mobility for users (3). Recent technological advancements have introduced a variety of materials, such as carbon fiber and thermoplastics, which contribute to lighter and more responsive prosthetic designs (2). These materials not only improve functionality but also allow amputees to engage in a wider range of physical activities. As the field continues to evolve, integrating smart technologies and sensors into prosthetic limbs has emerged as a promising avenue for further enhancing energy efficiency and adaptability to users' movements (4). The incorporation of advanced technologies, including electromyography (EMG) sensors and adaptive control systems, has proven pivotal in enhancing the energy efficiency of lower limb prostheses (5). These technologies enable prosthetic devices to respond dynamically to user movements, closely mimicking natural gait patterns and reducing the metabolic cost associated with walking.

As the emphasis on energy efficiency in lower limb prostheses continues to grow, researchers are increasingly examining the biomechanical implications of these development (6). The aim of this current review is to emphasize the vital role of personal care in the design and rehabilitation of prosthetic use and to emphasize providing appropriate solutions to increase the use of prosthetics.

Table 1. Summary of Selected Articles

Authors	Year	Prosthetic Type	Energy Consumption Focus	Key Findings
Kaufman *et al.*	2008	Smart Prosthetics	Impact of smart technologies on energy consumption	Smart technologies significantly improved energy efficiency and user satisfaction.
Mohanty *et al.*	2012	Custom Prosthetics	Impact of customization on energy consumption	Customization improved user comfort and reduced energy costs.
Huang *et al.*	2016	Various Prosthetics	Impact of materials on energy efficiency	The key factors affecting energy expenditure are the materials used in the orthotic devices and their designs."
Chin *et al.*	2017	Lightweight Thermoplastic Prosthesis	Reduction of metabolic costs in movement tests	Significant reduction in energy consumption during movement tests.
Zhao *et al.*	2017	Hybrid Prosthetics	Long-term use impact on energy efficiency	Long-term use led to sustained improvements in energy efficiency.
Bäuml *et al.*	2018	Carbon Fiber Prosthesis	Reduced energy consumption during movement	Significant reduction in energy consumption compared to traditional materials.
Alsarayreh, *et al.*	2020	Advanced Prosthetics	Comparison of energy consumption among designs	Advanced designs showed a 20% reduction in energy consumption.
Fleming, et al	2021	EMG-Controlled Prosthesis	Improved gait efficiency and reduced energy use	Enhanced gait efficiency and reduced fatigue levels in users.
Kim *et al.*	2021	Optimized Biomechanical Prosthesis	Improved energy efficiency with optimized design	Reduced metabolic rates in users compared to standard designs.
Pană, C.F *et al.*	2022	Smart Prosthetics	Adaptability and reduction of metabolic costs	Increased user adaptability led to reduced metabolic costs.

Materials and Methods

This literature review employed a rigorous approach to investigate advancements in lower limb prostheses and their impact on energy consumption during functional mobility for their users.

Search Strategy

A comprehensive search was conducted across multiple electronic databases, including PubMed, Scopus, and Web of Science, from January 2024 to November 2024. Specific search terms were utilized, including "lower limb prostheses," "energy consumption," "biomechanics," "smart prosthetics," "rehabilitation," and "metabolic efficiency." For the PubMed database, the search syntaxes; ("lower limb prostheses" AND "energy consumption") OR ("smart prosthetics" AND "rehabilitation") OR ("metabolic efficiency") were used. Boolean operators (AND, OR) were employed to refine the search results, ensuring a wide-ranging collection of literature pertinent to energy efficiency in prosthetic devices.

Inclusion and Exclusion Criteria

In the present study, reviewed articles specifically on lower limb prostheses, and studies that addressed energy consumption and efficiency metrics related to prosthetic devices were included. Non-peer-reviewed articles, including conference abstracts and opinion pieces, studies concentrating on upper limb prosthetics or non-lower limb devices, research not available in English or lacking sufficient methodological detail, Articles focused on non-ambulatory prosthetic applications were excluded.

Data Extraction

Data were extracted from the selected studies using a standardized extraction form. The focus was placed on the following key aspects: authors, year, and types of prosthetic devices, energy consumption focus, and key finding (Table 1).

Results

Our comprehensive search across three electronic databases yielded 90 articles. After removing duplicates and irrelevant articles, 54 records based on their titles and abstracts were remained. Of these, 44 were excluded because they did not meet our eligibility criteria, leaving 10 articles for a more detailed evaluation of their full texts. Further screening of these 10 articles led to the exclusion of 2 studies due to various reasons, including one that reported outcomes unrelated to energy consumption and another that lacked empirical data. This process resulted in the selection of 10 articles that ultimately met inclusion criteria and were included in qualitative synthesis, highlighting the significant impact of advancements in materials and prosthetic design on energy efficiency in lower limb prosthetics.

The selected articles in this review investigate the various effects of lower limb prosthetics on energy consumption. The results of a study demonstrated that carbon fiber prosthetics consume less energy during movement compared to traditional materials, which can lead to significant improvements in the quality of life amputees (7). One study identified key factors influencing energy efficiency, emphasizing the importance of material selection and prosthetic design (8) .

Furthermore, Pană *et al.* (9) showed that smart prosthetics with high adaptability can reduce metabolic costs, which is particularly important for users with specific needs. Fleming *et al.* (10) reported significant improvements in gait efficiency and reduced fatigue levels using EMG-controlled prosthetics, highlighting the potential of these devices to lower energy consumption. Another researcher compared energy consumption across different designs and found that advanced designs could reduce energy consumption by up to 20% (11). Kaufman *et al.* (12) discussed the impact of smart technologies on energy consumption, noting that these technologies not only enhance energy efficiency but also improve user satisfaction.

Zhao *et al.* (13) indicated that long-term use of hybrid prosthetics results in sustained improvements in energy efficiency. Chin et al. observed a significant reduction in energy consumption during movement tests using lightweight thermoplastic prosthetics (14). Mohanty *et al.* (15) found that customized prosthetics enhances user comfort and reduces energy costs too.

Finally, Kim *et al.* (16) reported that optimized biomechanical prosthetics lead to reduced metabolic rates in users compared to standard designs. These findings underscore the importance of optimized designs and advanced materials in reducing energy consumption and improving the quality of life for users.

Discussion

The findings of this literature review underscore the critical importance of continuous innovation in lower limb prosthetic technology. Recent development in materials, such as carbon fiber, have significantly enhanced the functionality and durability of prostheses, while also reducing the energy required for ambulation (11). These lightweight materials facilitate easier mobility and contribute to improved user comfort. Furthermore, the integration of smart technologies such as sensors and adaptive control systems represents a promising direction for future research. These systems can adapt to individual user needs in real time, optimizing energy efficiency and enabling a more natural gait (8). This evolution in technology highlights the importance of interdisciplinary collaboration among Medical engineers, Rehabilitation specialists, physician and researchers to examined what is important in the design of prosthetics is rarely. The emphasis on user-specific variables highlights the necessity for personalized approaches in prosthetic fitting and rehabilitation. Customization based on individual biomechanics, residual limb characteristics, and lifestyle can lead to significantly improved outcomes and a higher quality of life for amputees (15). Advances in 3D printing technology allow for the developing of tailored prosthetics that conform precisely to the anatomical and biomechanical needs of users. Studies indicate that personalized solutions enhance user satisfaction, fostering a sense of ownership and empowerment his overall well-being.

Additionally, the role of rehabilitation strategies in conjunction with advanced prosthetic technologies cannot be overlooked. Effective rehabilitation programs that incorporate strength training, gait analysis, and functional mobility exercises can complement the mechanical advantages of modern prostheses, leading to further reductions in energy expenditure during ambulation (15) .Future studies should aim to explore the synergy between prosthetic technology and rehabilitation practices to maximize the benefits for users, ensuring a holistic approach to recovery that addresses both physical and psychological aspects of users

The socio-economic implications of energy-efficient prosthetic devices warrant significant attention. As these technologies become more accessible, they hold the potential to improve the quality of life for a broader population of amputees, reducing healthcare costs associated with fatigue and mobility-related complications (7). Improved prosthetic designs enable amputees to return to work and engage actively in their communities, contributing to economic productivity and reducing reliance on social support systems. This holistic approach to prosthetic development, focusing on both technological advancements and user-centered care, will be crucial in shaping the future of lower limb prosthetics.

Looking ahead, the trajectory of research in lower limb prosthetic technology should focus on the continued development of energy-efficient devices while examining the holistic user experience. Investigating the long-term impacts of smart technologies on user mobility, psychological well-being, and social reintegration will be critical for informing future designs. Furthermore, examining the interplay between technological advances and user-centered design principles can yield insights that enhance both performance and user satisfaction.. As the field evolves, fostering a multidisciplinary approach that encompasses engineering, rehabilitation science, and behavioral health will be essential for driving innovation and improving outcomes for amputees.

To enhance the discussion on continuous innovation in lower limb prosthetic technology, it is crucial to promote interdisciplinary collaboration among medical engineers, rehabilitation specialists, physician and researchers, ensuring that user-centered design is prioritized by involving amputees in the development process. Emphasizing advancements in materials and smart technologies can lead to lighter, more adaptive prosthetics, while holistic rehabilitation programs should integrate physical therapy with prosthetic training for optimal outcomes. Additionally, conducting long-term impact studies on mobility and mental health will provide valuable insights, and advocating for policies that improve access to energy-efficient devices can significantly reduce healthcare costs and enhance quality of life for amputees.

Conclusion

In summary, the continuous innovation in lower limb prosthetic technology is vital for enhancing the functional performance and quality of life for amputees. Advances in materials and smart technologies are not only improving the mechanical performance of prostheses but also significantly reducing the energy required for ambulation. The emphasis on personalized fitting and rehabilitation strategies highlights the necessity of tailoring solutions to meet individual needs, thereby optimizing outcomes and user satisfaction. Furthermore, the socio-economic implications of these advancements underscore the potential for energy-efficient prosthetic devices to reduce healthcare costs and facilitate greater independence for users. As research progresses, a holistic approach that integrates technological advancements with user-centered care will be essential for shaping the future of lower limb prosthetics, ultimately leading to improved mobility, enhanced quality of life, and broader accessibility for all amputees.

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Ethical consideration

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Conflict of interest

None.

Authors' contributions

MR: supervision, data curation, formal analysis, investigation, and methodology, writing, original draft. AJ: supervision, resources, and writing, original draft.

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