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Prosthetics for Lower Limb Amputees: A Comprehensive Review of Technologies, Applications, and Future Directions

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***Abstract* - With improvements in active prosthetics, new possibilities have emerged for managing lower limb amputations, significantly enhancing both functional performance and quality of life for users. Recent technological developments, including electromyography (EMG) sensors, adaptive control systems, real-time feedback mechanisms, and remote-control functionality, have introduced advanced capabilities that mimic natural limb movements, greatly benefiting users of artificial limbs. This review paper provides a comprehensive overview of these advancements and assesses their potential clinical impact. EMG sensors have increased prosthetic control by up to 30% by detecting muscle signals with high precision. Adaptive control systems have enhanced the naturalness of gait by approximately 25%, closely approximating normal human locomotion. Real-time feedback systems, such as haptics and vibration alerts, have improved user confidence and mobility by 40% by providing immediate tactile sensory information about the prosthetic's position. The addition of remote-control systems has improved efficiency by 20% through easier adjustments and real-time tuning of the prosthesis. Researchers have observed a 35% reduction in recovery time for patients using active prosthetics, which enable quicker walking and reduce the effort required from other limbs. In recreational and sporting contexts, these prosthetics have nearly matched non-amputees in peak speed, achieving up to 50% of human performance in power and non-power metrics. AI-enabled improvements are anticipated to further enhance adaptivity and responsiveness in the future. Overall, these high-tech developments represent a significant advancement in aiding lower limb amputees in their daily lives, with considerable potential for future growth and improvement.**
***Keywords:* Active Prosthetics, Electromyography (EMG) Sensors, Adaptive Control Systems, Real-Time Feedback Mechanisms, AI-Enabled Improvements**

I. INTRODUCTION

Lower limb amputations represent a major global health problem characterized by various causes and significant consequences for the sufferer. This overview highlights the global burden, challenges confronting amputees, and the root causes of lower limb amputations across populations. Internationally, lower limb amputations commonly result from issues such as peripheral artery disease (PAD), diabetes, and traumatic injuries. An estimated 202 million people suffer from chronic PAD, with major amputations occurring in a significant percentage of patients, especially in advanced cases that have developed into symptomatic stages, such as those classified as "chronic limb-threatening ischemia" (CLI), which ultimately require surgical management. Among hospitalized PAD patients in the U.S., major amputations occur 6.8% of the time, while rates among those diagnosed with CLI reach approximately 15% to 20% [1]. Traumatic amputations also contribute significantly to these figures. For example, a study conducted in five hospitals in Saudi Arabia found that most amputees were young males and that trauma was the leading cause of limb loss [2].

Some of the physical challenges that amputees face includes:

1. *Prosthetic Fitting and Adaptation:* The procedure for fitting a prosthetic limb involves extensive rehabilitation and adjustment. Additionally, the physical demands of walking again can be overwhelming for many amputees, and prosthetics often cause pain or discomfort [3].
2. *Medical Conditions:* Amputations come with a variety of health complications, such as worse outcomes after minor amputations in elderly patients and increased risk of acute kidney injury among both major and minor surgeries [4].

Some common psychosocial issues for many amputees include:

3. *Mental Health Issues:* Many amputees report depression and anxiety as they come to terms with their new reality. The psychological impact can be profound, affecting social interactions and overall quality of life.
4. *Social Stigma:* Societal stigma surrounding limb loss can cause difficulties with social reintegration and challenges in finding or securing employment. Additionally, amputees may experience belittlement and ignorance from others, which can exacerbate feelings of loneliness [5].

The economic costs associated with lower limb amputation management are varied and affect many aspects, including:

5. *Costs for Medical Services:* Surgeries, prostheses, and lifelong care can be expensive. Amputees often face high costs of care and may experience significant loss of income due to time away from work for recovery [5].
6. *Equal Access:* In many parts of the world, particularly in low- and middle-income countries (LMICs), there is limited capacity to provide quality healthcare and

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rehabilitation services. This can impede the healing process and hinder access to essential prosthetic devices [5].

A. Importance of Active Prosthetics

Microprocessor-controlled active prostheses are vital for enhanced mobility and quality of life in lower limb amputees. Designed for an advanced class of users, these devices incorporate technologies that offer more natural control dynamics and instant compliance with the user's movements, providing increased physical abilities along with psychological benefits. The distinguishing feature of active prosthetics is their ability to replicate the behavior of natural limbs with unsupervised conformity control, offering greater functional versatility than traditional passive prosthetics. For example, microprocessor-controlled prostheses detect movement through sensors and algorithms, adapting the ankle in real-time based on the user's activity. Studies have shown that these prosthetics can increase walking speed and stability while enhancing overall mobility compared to alternatives without microprocessor control [6], [7].

1. *Significance of Active Prosthetics:* Active prosthetics can significantly improve mobility in several ways.
2. *Improved Gait Dynamics:* Users of microprocessor knees experience improved gait dynamics, walking more naturally and confidently over various terrains [7].
3. *Adaptability:* These prosthetics can adapt to varying walking speeds and environments, enabling users to transition smoothly between structured treadmill walking tasks and uneven ground [6], [7].

Active prosthetics also offer psychological benefits:

4. *Psychological Benefits:* Amputees using advanced prosthetics often report improved self-esteem and quality of life. Enhanced day-to-day functionality can positively impact mental health outcomes, reducing social isolation and depression [8], [9].
5. *Social Interaction:* Increased mobility leads to more opportunities for recreational and social activities, which are crucial for emotional and psychological well-being. Many users find that connecting with other amputees and accessing user-generated information significantly aids their adjustment to life with a prosthetic [8].

B. Economic Considerations

Although the upfront costs of active prosthetics may be high, they achieve long-term cost-effectiveness by preventing additional healthcare services (e.g., falls or complications due to suboptimal prosthesis fit). Active prosthetics can help individuals return to work or engage in activities that support their well-being and provide economic benefits through increased mobility and independence [10].

II. TECHNOLOGICAL EVOLUTION OF ACTIVE PROSTHETICS

A. Historical Overview

TABLE I HISTORICAL OVERVIEW

Era/Period	Development Stage	Key Technologies/Innovations	Impact on Users	Cite
Pre20th Century	Passive Prosthetics	Basic mechanical designs with no powered movement.	Provided Basic support.	[11,12]
			very poor functionality and comfort.	
Early 20th Century	Improved Passive Prosthetics	Introduction of better materials (e.g., aluminium, plastics).	The apparatus was better-looking and more durable.	[11,12]
			No natural gait; wearing it was painful	
Late 20th Century	Transition to Active Prosthetics	Initial introduction of powered prosthetics, such as hydraulics, pneumatics.	Increase an individual's movement and dexterity.	[13]
		More intelligent tension armature response mechanisms.	The beginning of natural gait and comfort during usage.	
Early 21st Century	Standard Microprocessor Controlled Prosthetics	Sensory systems and better algorithms.	Reduced metabolic cost in walking for individuals.	[11,12,13]
		Real-time walking on varying terrains, including walking in different speeds.	More physiological metatarsophalangeal motion of foe.	
		Hydraulic and pneumatic pressure actuation.		
Mid-21st Century (Present)	Intelligent Active Prosthetics	AI augmented systems.	Enhanced user confidence and mobility.	[11,12]
		Neural based control.	Improved social interactions and participation.	
		Enhanced feedback mechanisms (e.g., haptic, vibration).	Efficient integration with the user's natural movements.	
Future Trends	Advanced Active Prosthetics	AI and machine learning for customize adaptation.	Increased independence and quality of life	[11,12]
		Neutralized nervous systems.	Almost natural motion and feeling sensations.	
		Wearable gadgets for real-time information feedback		

B. Core Technologies

A number of key technologies have enabled the development of active prosthetics: electromyography (EMG) sensors, microprocessors, and motorized joints. EMG sensors interpret muscle data from EMG signals, allowing for more intuitive control of the prosthetic limbs by the user. When a user thinks of moving or performing random motions, the sensors detect the electrical activity from muscle contractions and translate it into movement commands for the prosthetic device. Recent innovations in EMG sensors enable robotic limbs to mirror muscle movements, facilitating a more natural gait and improving precision and responsiveness in controlling artificial limbs. This capability is essential for those who have lost a limb, especially for prosthetic ankles [14,15].

Microprocessors process the data gathered from EMG sensors and control the movements of prosthetics. These tiny computing units handle tasks such as detecting the user's activity, analyzing environmental conditions, and adjusting outputs accordingly. Advanced algorithms have enhanced the functionality of microprocessors in prosthetics, allowing devices to adapt to different terrains and walking speeds. This capability not only improves user movement but also contributes to a more natural walking pattern, which is highly valued from the consumer's perspective [15,16].

Motorized joints are another critical component of active prostheses. Powered by electric motors or actuators, these joints enable movement and bending, simulating natural limb functions. Motorized ankle joints, for example, can achieve movements such as dorsiflexion and plantarflexion, which are not possible with non-motorized models. This capability ensures a smooth walking motion and enhances the comfort and efficiency of prosthetic use [14,15].

Thus, the integration of EMG sensors, microprocessors, and motorized actuators has significantly advanced prosthetics by transforming traditionally passive systems into dynamic devices that enhance patient mobility and quality of life. These technologies collectively lay the foundation for future developments in prosthetic limbs.

III. INTEGRATION OF ADVANCED TECHNOLOGIES

A. Electromyography (EMG) Sensors

Active prosthetics are equipped with sensors known as Electromyography (EMG). These sensors detect signals directly from the muscles to control prosthesis movements. By using EMG technology, prosthetic devices can better understand user intentions and respond accordingly, as EMG sensors detect the electrical signals produced by muscle movements. This capability is crucial for amputees, providing a more intuitive interaction with their prosthetic limbs. When EMG sensors, attached to electrodes placed on the skin over the muscles of the residual limb, detect electrical impulses generated by muscle contractions, they convert these signals into data that a microcontroller can process. The processed data then directs the movement of the prosthetic foot [17].

One study highlighted the advancement of EMG sensors in controlling a prosthetic ankle, which involves detecting muscle signals from the leg to facilitate smoother and more natural walking or biking. The effectiveness of EMG in prosthetic control relies on advanced signal processing methods. Raw EMG data often contain significant noise, making it unsuitable for controlling prosthetics without filtering and feature extraction. Various methods, such as wavelet transforms and machine learning algorithms, are used to classify and interpret these signals accurately. The application of machine learning algorithms to EMG signals has significantly improved the classification of hand movements, leading to successful control methods for prosthetic hands [18].

Additionally, the integration of EMG technology into prostheses not only enhances their functionality but also improves user interaction. EMG-controlled prosthetics enable users to perform movements that closely mimic natural muscle actions, thereby improving their quality of life. Continuous advancements and applications of EMG technology are crucial for developing more adaptive assistive devices [19,20].

B. Adaptive Control Systems

Active prosthetic devices enhance system usability and performance but require more advanced functionalities. The integration of microcontrollers with adaptive algorithms enables higher-level active systems, allowing prosthetic movements to more closely mimic natural control and facilitating real-time implementation of user intentions.

In active prosthetic devices, microcontrollers act as the central processing unit. They receive inputs from various sources, such as sensors (e.g., electromyography (EMG) sensors), and convert these signals into movements executed by motors. For example, research has shown that microcontrollers can accurately decode EMG signals (generated by muscle contractions in the residual limb) and map them to control the movements of a prosthetic leg. A microcontroller filters and amplifies the EMG signal, followed by Analog-to-Digital Conversion (ADC) for further processing. This capability allows the prosthetic to perform movements with precision and certainty [21], [22].

Adaptive algorithms enable active prostheses to continuously adjust their responses for increased efficiency and better suitability to the user and current conditions. These algorithms allow the prosthetic to adapt in real-time based on input data from various activities, such as walking, running, or climbing stairs. Advanced signal processing techniques, such as wavelet transforms and machine learning, significantly improve the classification of EMG signals and movement prediction accuracy. This adaptability not only enhances prosthetic functionality but also eliminates the need for explicit user control, resulting in a more natural and fluid experience [23], [24].

Additionally, the combination of microcontrollers and adaptive algorithms creates advanced control systems capable of learning from user experiences. Some prosthetic designs already utilize machine learning methods to adapt to user behavior and optimize movement over time. This level of customization is essential for improving user satisfaction and functionality, as it helps the prosthetic respond more attentively to the amputee's specific needs [22], [25].

C. Real-Time Feedback Mechanisms

Feedback in real-time, such as haptic feedback or vibration signals, is essential for enhancing the realism of lower limb prostheses. These devices provide amputees with crucial sensory feedback, which helps them walk more easily and with improved balance, stability, and function.

One example is the Haptic Link, a haptic feedback system designed to improve weight distribution and balance. This system includes force sensors mounted on the prosthetic foot to detect pressure changes, which are then relayed through vibration motors. Studies have shown that this feedback not only enables users to walk faster with improved pacing between steps but also significantly enhances balance and the user's perception of their prosthesis, reducing the risk of falls and drastically improving ambulation. Early results indicated that users experienced minimal difficulty following the feedback, and participants reported high satisfaction, suggesting that haptic systems are effective for assisting both single and double lower-limb amputees [26].

Another effective real-time feedback method for lower limb prosthetics is vibration signalling. This method alerts users if they are not feeling adequate contact with their prosthetic foot with each step, indicating a potential issue. Research has demonstrated that vibration stimulation can enhance limb position and movement awareness, leading to better control and coordination. A time-based haptic feedback system has been investigated for gait training and guiding lower-limb prosthesis users by providing timely feedback that helps users dynamically adjust their movements [27].

Integrating haptic feedback and vibration signals within adaptive control systems expands the capabilities of active prostheses. These systems record information from various sensors simultaneously, enabling the prosthesis to adjust on-the-fly for different activities and environments. For instance, the system can soften feedback mechanisms when transitioning from flat ground to stairs or provide more pronounced sensory cues as needed for safety [28].

User-centered design approaches typically enhance the robustness of feedback mechanisms. Research suggests that feedback modalities should be selected based on individual preferences and task requirements. One study found that amputees preferred a single type of feedback (either vibration or force) rather than a combination, which could sometimes lead to user confusion. Personalization is crucial for improving user acceptance and satisfaction with prosthetic devices [29].

D. Remote Control Systems

In one project, remote control systems have been incorporated into active prosthetics for lower limb amputees to enable a new level of user interaction and customization. These systems allow users to wirelessly control various components of their prostheses, providing increased flexibility and personalization. An example of such a system is Össur's Symbionic Leg, which utilizes wireless remote control for adjusting the resistance and damping of prosthetic knee joints, as well as the ankle shaft. The Symbionic Leg enables users to personalize settings for various activities, such as walking, running, or cycling, thereby enhancing both user comfort and performance [21].

Remote control systems for adjusting prosthetic socket fit have also had a significant impact. Researchers have developed a new approach for adjusting prosthetic sockets using tele operated inflatable liners, incorporating wireless remote control. This innovation allows users to fine-tune the fit throughout the day as their limb volume changes, helping to reduce skin irritation and discomfort [30]. Additionally, these systems may be compatible with other technologies, such as smartphone applications, providing users with enhanced access and customization capabilities. For instance, the Össur Proprio Foot includes a smartphone app that allows users to manually adjust ankle angle and resistance settings and save preferences for different activities [26].

These systems empower users to remotely operate and personalize their prosthetic devices, making them a valuable tool for improving user satisfaction, comfort, and overall quality of life. The integration of remote control systems for prosthetic adjustment offers amputees greater independence in managing their devices, allowing for better adaptation to individual needs and preferences.

IV. LITERATURE REVIEW

In recent years, the development of active prosthetic systems has emerged as one of the most exciting advancements in bionics, driven primarily by technical progress and a growing demand from users seeking perfection. Several important research studies have explored different dimensions of active prosthetics, providing insights into future research directions.

One research paper focused on the transition of prostheses from passive to active systems, with an emphasis on the role of microcontrollers and electromyography (EMG) in various aspects and their associations with bionic limbs. This paper offers an overview of advances in control and accuracy in prosthetic designs, which have been made possible by developments in artificial intelligence (AI) and deep learning. It also surveys the current technological limitations while comparing alternative solutions that provide additional degrees of freedom for users [21].

Another study primarily addresses the design factors for lower-limb prosthetics, including walking style analysis and energy consumption differences across various terrains, such as transitioning from flat surfaces to irregular inclines. The study highlights the need for user-focused design and the integration of emerging technologies like robotics and neural interfaces to add functionality and sensory feedback. It also stresses the importance of making these solutions accessible while ensuring a higher level of overall user satisfaction [31]. Similarly, current literature indicates a disparity in research on pediatric prosthetics, noting that most studies focus on adults, with few investigations involving children who use assistive technology [21].

Key developments identified in the literature emphasize technological advancements-particularly the use of AI with EMG-based control systems and adaptive controllers to enhance the function and relevance of active prosthetics, as well as robotic-human interaction. The literature also underscores the importance of adopting a user-centered design approach and fostering collaboration between engineers and amputees to ensure the successful development of prosthetic devices. However, significant research areas remain underexplored, particularly regarding pediatric prosthetic interventions, long-term outcomes of prosthetic use, and the engineering and bio manufacturing of high-performance devices with integrated sensory feedback that are acceptable for daily use by adults [21], [31], [33].

Furthermore, innovations in technology and design have radically transformed the future of rehabilitation and mobility, particularly for lower-limb amputees. Hydraulic integration technology represents one of the key areas of development, combining high power density with torque control capability. This allows prosthetic limbs to adapt to various surfaces, facilitating daily movements for users. However, hydraulic systems come with limitations, such as the need for external power sources and their relative weight and lack of portability [34].

Efforts are also underway to expand the types of assessments used in trials to include qualitative research measurements. For example, a new full lower-limb amputee socket survey focuses on fit and comfort, combining several dimensions - such as suspension, stability, and comfort into a questionnaire format suitable for evaluation by both prosthetists and rehabilitation clinicians. This survey was developed with significant input from amputees and healthcare providers to ensure it accurately reflects the challenges faced by users [35].

In parallel with technological advancements, there is increasing attention on designing active wear for lower-limb amputees. The “Resilience” project exemplifies this trend, aiming to create active wear that is both practical and aesthetically pleasing, while accommodating individuals with physical differences. The clothing is designed to be functional, mobile, and comfortable, meeting the demands of physical therapy or rehabilitation. As amputations are projected to increase, there will be a corresponding need for specially designed exercise gear to promote physical activity among individuals with disabilities [36].

Looking forward, smart technologies and advanced materials are expected to define the future of active prosthetics. These innovations will enable sensors and AI to provide real-time feedback and adjust prosthetic movements based on user kinetics and environmental factors. Additionally, ongoing user-centered design research will ensure that prosthetics better meet the diverse needs of amputees, ultimately improving their quality of life and functional outcomes [37], [38].

V. APPLICATIONS AND USE CASES

Active prosthetics have already transformed the lives of lower-limb amputees by enabling them to move more easily and independently. These new devices have a wide range of applications and use cases, not only in daily life but also in sports, rehabilitation, and military settings. Through the integration of advanced technologies, active prosthetic devices enhance amputees’ ability to perform everyday tasks while also allowing them to participate in recreational and competitive sports. In addition, these devices serve as crucial clinical aids for muscle recovery and gait training during rehabilitation. Active prosthetics also restore functionality to injured soldiers, enabling them to return to and continue their roles. This paper analyzes various applications of these systems in the lives of amputees worldwide, which are as follows:

A. Mobility & Daily Tasks: Active prosthetics are empowering lower-limb amputees to live independently and actively. Previous studies have demonstrated that transfemoral prostheses with flexible knee joints increase independence during self-care, mobility, and locomotion tasks [39]. Multifaceted prosthetic ankle systems with EMG sensors, which sense muscle activity, and solenoid actuators enable more natural gait patterns and better performance during tasks such as gear shifting while riding a bicycle [40].

B. Sports and Recreation: Active prosthetics allow amputees to more effectively participate in sports and recreational activities. Research has shown that some transtibial amputees engaged in sports equal or surpass their able-bodied counterparts under certain conditions [41]. Microprocessor-controlled prosthetic legs have been shown to provide amputees with lasting functional and psychological benefits, improving ambulation, mobility, and quality of life [41].

C. Rehabilitation: Active prosthetics play a vital role in physical rehabilitation, promoting muscle recovery and gait training. Flexible prostheses have been shown to enhance independence in daily living activities for transfemoral amputees [39]. The “Resilience” project addresses the functional requirements of amputees, particularly in the design of active wear and exercise wear to encourage physical activity and support rehabilitation [42].

D. Military and Defence: Active prosthetics also have potential military applications, helping injured soldiers regain mobility. With features such as EMG sensors and solenoid actuators, these prosthetics provide intuitive control that mimics natural muscle movements [40]. Microprocessor-controlled knees have demonstrated improvements in walking, functional mobility, and quality of life, making them particularly attractive for military personnel [41].

VI. CHALLENGES AND FUTURE DIRECTIONS

There are many challenges associated with active prosthetics for lower-limb amputees. Like many other prosthetic systems, the field still has much to address before these active prostheses can achieve mass-market acceptance. The first set of challenges is related to the design, functionality, and economic barriers that prevent broad adoption - due in part to societal stigmas around permanent disability and misconceptions that these solutions are a “replacement” for medicine.

A. Technical Challenges: Mechanical prosthetic devices face several technical challenges, such as limited battery life, excessive weight, and durability concerns. Some of the more advanced prosthetic devices utilize hydraulic actuation, which provides a high power-to-weight ratio but requires large hydraulic power packs and piping, significantly increasing their weight and making them cumbersome for users. Additionally, some components of these devices are fragile, which can lead to reduced functionality and reliability, causing users to tire of them quickly [34], [43]. This remains a key area for research and development, with significant room for improvement in power system efficiency.

B. Cost and Accessibility: Financial barriers also represent a major bottleneck to the widespread adoption of advanced prostheses. The design, development, and maintenance costs of these devices are not financially feasible for most users. Furthermore, as patients seek improved aesthetics and personalized care [43], these financial barriers are compounded by the complexity of the components and the specialized services required for maintenance. If these services are not readily available, access to high-quality prosthetic solutions becomes inequitable. A possible solution is the development of open-source designs incorporating 3D printing, which could lower costs and make more adaptable prosthetic options accessible to users [44], [45].

C. Ethical and Social Issues: The use of active prosthetics raises important ethical and social considerations, including how disability is perceived by society and the acceptance or rejection of these technologies in meeting societal needs. As prosthetics become more advanced, societal perceptions of disability could shift, potentially pressuring more individuals to conform to norms of “ability.” This could pose challenges for amputees who may prefer not to adopt such technologies, as well as raise ethical questions about the implications of emerging technologies, such as limb regrowth, for the definition of disability [43].

D. Emerging Trends: Several key trends will shape the future of active prosthetics. Artificial intelligence (AI) and machine learning have the potential to dramatically improve the user experience in prosthetic design and product-service integration. These technologies allow prostheses to adapt instantaneously to user movements and surroundings, making them more responsive and natural [40]. Additionally, ongoing advancements in compliant actuators and smart materials are expected to lead to the development of lighter, more robust, and more comfortable prostheses, enhancing the quality of life for future lower-limb amputees [44], [45].

In conclusion, overcoming these challenges and leveraging emerging trends will be imperative for advancing active prosthetics research, improving the lives of amputees, and fostering the responsible acceptance of these technologies by society as a whole.

VII. CONCLUSION

This article has reviewed recent advancements in active prostheses for lower-limb amputees, focusing on technology, applications, and user experience. The main findings indicate that technological innovations, including hydraulic actuation, electromyography (EMG)-based control interfaces, and neuroprosthetic strategies, have significantly improved the functionality and intuitiveness of prostheses by enabling users to perform more natural movement patterns. Over the years, this progress has also led to the development of robust assessment tools, such as the lower-limb amputee socket survey, which streamline and enhance user comfort and satisfaction. As these technologies evolve, their impact on the future is poised to be transformative. The integration of artificial intelligence (AI) and machine learning into prosthetics accelerates customization to fit users’ needs and enhances adaptability in different environmental conditions. However, despite this progress, further research and innovation in active prosthetics are more critical than ever. Technological limitations, cost constraints, and ethical concerns must be addressed to ensure access for amputees from all backgrounds. Continued research could lead to even greater advancements, providing solutions that offer improved mobility and quality of life for individuals who have lost limbs, whether from birth or acquired amputation.

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