Power Sources of Prostheses and Technological Advances in Prosthesis Design

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ABSTRACT

Losing a limb significantly impacts daily life by affecting human mobility, causing mundane activities to suddenly become strenuous. Amputations have become an increasing global problem as the number of traumatic amputations has increased from about 370 million in 1990 to 552 million in 2019 [1]. The need for suitable and comfortable prostheses has become more apparent with the rising number of amputations. The two types of core power sources used in upper limb prostheses, body power and myoelectricity, have significantly improved over time through the advancement of sensor technology and CAD (computer-aided design). This review will compare and contrast the different types of power sources available for upper limb prostheses and detail the advancement of sensors and the influence of CAD on prosthesis design.

INTRODUCTION

Prostheses are artificial devices that replace missing limbs or body parts, helping individuals regain function and mobility. According to the Amputee Coalition, approximately 5.6 million people live with limb loss in the United States alone, with an estimated 185,000 amputations occurring each year. Among those with upper limb amputations, a significant proportion seek prosthetic solutions to improve their quality of life.

There are two primary types of upper limb prostheses: myoelectric and body-powered. **Myoelectric prostheses** are advanced devices that use electrical signals generated by the user’s muscles to control the movement of the prosthetic limb. These signals are detected by electrodes placed on the skin over the remaining muscles in the residual limb. The prosthesis interprets these signals to perform various functions, such as opening and closing the hand, rotating the wrist, or bending the elbow. In contrast, **Body-powered prostheses** are mechanically operated using the user’s body movements. A harness and cable system controls these devices. When the user moves their shoulder or another part of their body, the tension on the cables translates into movements of the prosthetic limb.

This review paper aims to build and expand on previous research in the field of upper limb prostheses, focusing on publications from 1921 to 2024 [2]. These studies describe significant developments in prosthetic technologies utilizing electroencephalogram (EEG) and electromyogram (EMG), which are leading methods for controlling both body-powered and myoelectric prosthetic limbs [3, 4]. Additionally, past reviews have highlighted these control systems' key features, advantages, and disadvantages. For instance, body-powered prostheses are praised for their reliability, durability, and affordability, while myoelectric prostheses are noted for their advanced control and aesthetic appeal.

The review will introduce the mechanisms underlying body-powered and myoelectric prostheses and explore the technologies that aid in their design and functionality. This includes focusing on sensors used in myoelectric prostheses and the role of Computer-Aided Design (CAD) in enhancing socket design and patient comfort for body-powered prostheses [9]. Recent advancements in prosthetic sensors have aimed at improving EMG signal detection accuracy and enhancing sensory feedback, which has significantly improved users' ability to perform delicate tasks with myoelectric prostheses [5, 6].

While body-powered prosthetics have seen incremental progress, many advancements have yet to be widely adopted due to amputees' preferences for these devices over externally powered options [12]. This preference highlights the importance of reliability, durability, and simplicity in body-powered prostheses. In contrast, myoelectric prostheses have advanced considerably in EMG signal acquisition and processing; however, these systems often require extensive training and face challenges due to signal variability from changes in limb position and muscle contractions [8, 11]. Despite their advanced capabilities, myoelectric prostheses remain more expensive and high-maintenance than body-powered ones.

The central goal of this review is to evaluate the efficiency of these two power sources for prosthetic arms and understand the reasons behind prosthetic abandonment. By analyzing user case studies and existing polls, this review aims to determine the most practical applications for each type of prosthesis and the factors influencing their adoption. This comprehensive analysis will provide a broader perspective on the field of upper limb prostheses, combining the strengths and challenges of both body-powered and myoelectric technologies.

METHODS

Literature Search

The Google Scholar database was utilized to conduct a comprehensive literature search for a review paper on recent advancements in upper limb prosthesis technology. Key terms entered into the search field included: "prosthesis sensors," "myoelectric prostheses," “body-powered prosthesis,” “global amputations,” "upper limb prostheses," “CAD in prosthetics,” and similar terms that correlate to the studied field. Using these terms, multiple searches were conducted to gather a wide range of scholarly articles, including review and research papers, focusing on those published within the last 20 years to ensure the most relevant information. The researcher reviewed the article’s abstracts and conclusions to assess their relevance and contribution to the topic. Additionally, attention was paid to highly cited papers and recent conference proceedings, as these often indicate significant advancements and emerging trends in the field. By organizing the findings from these sources, the research aimed to develop a thorough understanding of the current state of exploration in the field of upper limb prostheses and identify key areas for future investigation.

RESULTS

Power Sources

Body-Powered Mechanisms

Body-powered upper limb prostheses operate through a system of cables and harnesses that utilize the user's bodily movements to control the prosthetic limb. The most common mechanism involves a shoulder harness, which is connected to a cable system. When the user moves their shoulder or upper arm, the cable is pulled, creating tension that translates into movement of the prosthetic hand or arm, where the residual limb rests in a socket [14]. This direct mechanical link allows for a relatively simple and sturdy design, giving the user immediate feedback and control over the prosthetic limb. This system's simplicity and mechanical nature make it highly durable and reliable, especially in demanding environments where electronic systems might fail.

The control mechanisms in body-powered prostheses are typically divided into two primary types: voluntary opening and voluntary closing devices [23]. In voluntary opening systems, the default state of the prosthetic hand is closed, and the user exerts tension on the cable to open the hand, a system shown in Figure 1. Conversely, in voluntary closing systems, the default state is open, and the user must exert tension to close the hand. Each mechanism offers distinct advantages; voluntary opening devices are generally preferred for their ability to hold objects without continuous exertion, while voluntary closing devices can provide a stronger grip for tasks requiring significant force. The mechanical feedback from these systems allows users to develop a nuanced control over their prosthesis through practice and muscle memory, leading to more efficient and effective use in daily activities.

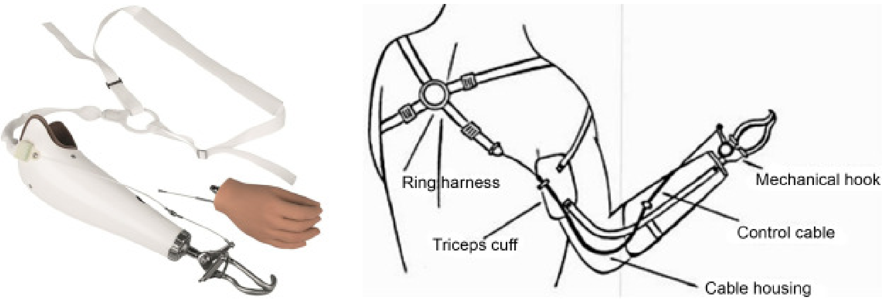

Figure 1 [21]
Diagram of a body-powered upper limb prosthesis utilizing a harness, control cable, and mechanical hook

Myoelectric Mechanisms

Myoelectric upper limb prostheses use electrical signals generated by the residual muscles in an amputee's limb to control the movements of the prosthetic device. These electrical signals, known as electromyographic (EMG) signals, are detected by sensors placed on the skin surface over the muscles. When the user intentionally contracts these muscles, the sensors capture the resulting EMG signals, which are then processed by an onboard microcontroller. Figure 2 displays an example of a myoelectric upper limb prosthesis and where sensors may potentially be located. Advanced algorithms, often incorporating machine learning and pattern recognition techniques, analyze these signals to determine the intended movements [18]. This processed data is then translated into precise movements of the prosthetic hand or arm, allowing for a range of actions from simple grasps to complex manipulations.

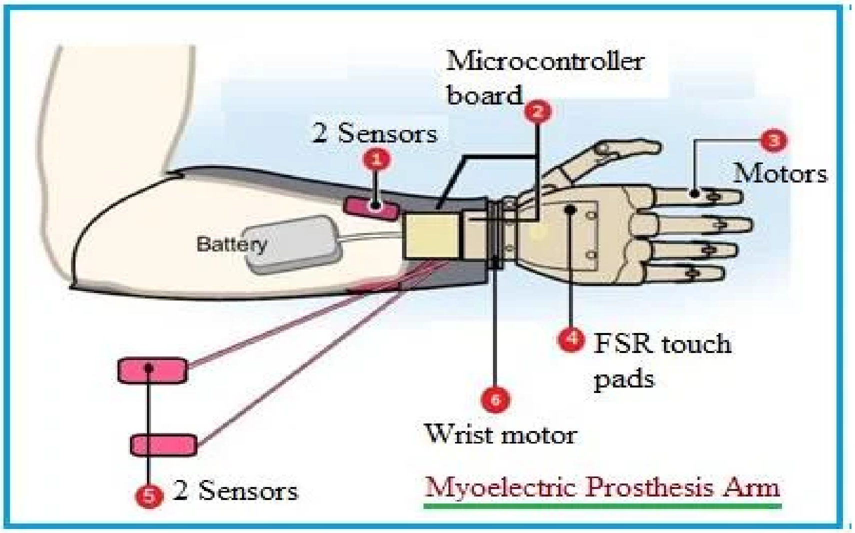

Figure 2 [24]
Example diagram of a myoelectric upper limb prosthesis with motors, sensors, haptic touch pads, and control board

The effectiveness of myoelectric prostheses hinges on the accuracy and reliability of EMG signal acquisition and processing. Surface EMG, or sEMG, sensors are commonly used due to their non-invasive nature. However, they can be prone to signal interference from external factors such as sweat, movement, and electrode displacement. To mitigate these issues, researchers have developed robust algorithms and multi-modal sensor configurations that enhance signal stability and reduce noise [4]. Additionally, the integration of sensory feedback mechanisms provides users with real-time feedback on grip strength and object texture, significantly improving the usability and functionality of the prosthesis. These technological advancements have led to myoelectric prostheses that offer more natural and intuitive control, increasing user satisfaction and expanding the potential for more precise movements.

Prosthetic Technologies

Electrograms

Electroencephalography (EEG) and electromyography (EMG) are pivotal technologies in the advancement of myoelectric upper limb prostheses. In Figure 3, an EEG reading graph demonstrates the electrode sensors capturing brain waves. EEG-based systems capture brain signals to interpret intended movements, offering the potential for intuitive control methods that do not rely on residual muscle function alone. This approach holds promise for individuals with high-level spinal cord injuries or amputations where traditional EMG may not be viable. Conversely, EMG detects electrical signals from residual muscles in the amputated limb, allowing precise control of prosthetic movements based on muscle contractions [4]. Together, these technologies contribute to the development of prosthetic limbs that offer more natural and effective control, enhancing the quality of life for prosthetic users by enabling intuitive and dexterous movement.

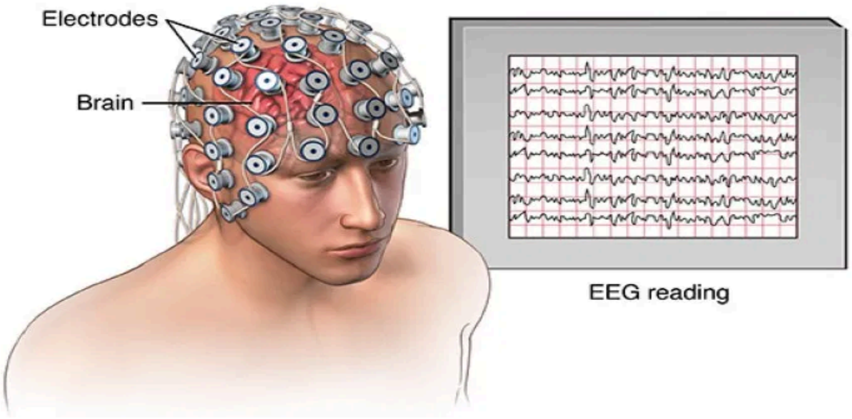

Figure 3 [24]

Example diagram of an EEG reading graph and small metal disc sensors with thin wires pasted onto the scalp

Upper Limb Prosthesis Sensors

Sensors are integral components in myoelectric upper limb prostheses, crucial for detecting and translating muscle activity into control signals for artificial limbs. sEMG sensors are commonly used to capture electrical signals generated by residual muscles during muscle contractions, forming the basis for real-time control of prosthetic movements [5]. These sensors are placed on the skin's surface over relevant muscle groups and utilize signal processing techniques to interpret muscle activation patterns. Recent advancements in the development of sensors include the integration of advanced signal processing algorithms and multi-modal sensor configurations, which enhance the reliability of prosthetic control. Additionally, tactile and force sensors are employed to provide sensory feedback, allowing users to perceive grip force and object characteristics, and improving the prosthesis' functionality and user experience [8]. These sensor technologies continue to evolve, aiming to optimize prosthetic performance and user standards in everyday activities.

Computer-Aided Design and Computer Aided Manufacturing

Computer-aided design and computer-aided manufacturing (CAD/CAM) technology has revolutionized the field of upper limb prosthetics by significantly enhancing the design, customization, and fabrication processes of prosthetic devices. CAD/CAM systems allow prosthetists and engineers to create precise and personalized prosthetic components based on digital scans of the residual limb. This technology facilitates the prototyping process, enabling adjustments and optimizations to fit individual anatomical characteristics more accurately, such as tailored socket designs for residual limbs. Moreover, CAD/CAM advancements have streamlined production times and improved the overall quality and comfort of prosthetic devices, leading to higher levels of patient appeasement [10]. As the technology continues to evolve, future developments are expected to focus on further integrating CAD/CAM with advanced materials and manufacturing techniques, potentially lowering costs and expanding accessibility to more tailored and effective upper limb prosthetic solutions.

Myoelectricity vs. Body-power

Myoelectric prostheses generally offer more natural and versatile control, leading to higher user satisfaction in performing complex tasks. However, they require more training, maintenance, and are often costlier. In contrast, body-powered prostheses are praised for their reliability, durability, and lower cost, making them favorable for users who prioritize simplicity and robustness over advanced functionality. The drawbacks to

body-powered prostheses are a lack of cosmetic appearance, limited versatility, and physical discomfort, as they often require strenuous physical effort to control [12].
In a case study conducted in 2018, the performance and suitability of a bionic hand were compared to a customized body-powered prosthesis in a user with a highly demanding work environment. The outcome of the experiment was that the bionic hand significantly improved the user's ability to perform tasks requiring fine motor skills and precision due to its advanced control and natural range of motion. However, it was prone to mechanical failures and required frequent, costly maintenance, making it less practical for the challenging setting. In contrast, the customized body-powered prosthesis, although offering less sophisticated control, was highly durable and reliable, easily withstanding the physical rigors of the user's job. User feedback emphasized the critical need for prostheses that balance advanced functionality with low maintenance requirements [13].

User Enhancement

Enhancing user experience and functionality in upper limb prostheses involves addressing the diverse needs and challenges users face. Many studies highlight the importance of understanding the ergonomic and control difficulties some users encounter with myoelectric devices, emphasizing the need for personalized training and device optimization to improve usability [10]. In contrast, certain case studies underscore the benefits of body-powered design approaches, comparing the practical advantages of a bionic hand versus customized body-powered technology in demanding work environments. These studies emphasize the critical role of user feedback and customization in developing prosthetic solutions that meet individual functional requirements and enhance user satisfaction [13]. Furthermore, research on individuals' journeys in learning to use a body-powered prosthesis reveals how users' adaptation to body-powered devices leads to improvements in functionality over time, underscoring the importance of tailored rehabilitation programs to optimize prosthetic performance and user integration into daily activities [14].

Pros and Cons of Each Power Source

[1, 7, 10, 12, 13]

PROS and CONS

Body-Powered	Myoelectric
● BP hooks are better suited for working conditions (more durable) ● Shorter training time ● Less adjustments and easier to clean ● More comfortable	● Improved cosmesis/aesthetic appearance ○ improved psychosocial and social adaptation ● Ability to handle larger-diameter objects

• Function with less sensitivity to fit • Less expensive	• Easily grasp small objects • Reduces phantom limb pain
• Low wrist control and movement • Harness suspension systems with cable controls can be visible through and damaging to the user's clothing • Irritation to skin on back and underarm • Slower movement • Poor grasp force • Cable and harness maintenance issues	• Used for only light work • Longer training/adjustment time • More expensive (both the prosthesis and the healthcare costs of training) • Offers little proprioceptive feedback or information regarding joint position, speed of movement, and grip force • Bulkier and heavier • Less reliable/durable

CONCLUSION

Body-powered prostheses are generally praised for their robust and effective functionality, consisting of lightweight materials, resulting in a more cost-efficient option. Additionally, body-powered prostheses require a shorter training time due to their simplified open-close grasp system, which is generally considered easier to learn. However, the drawbacks to this power source include lower wrist control and irritation to the epidermis on the back and axilla due to chaffing from the harness and straps, which may damage the user's clothing. Myoelectric prostheses are sought after for their cosmetic enhancement as they resemble a human arm more closely than the hooks of body-powered prostheses, resulting in improved social adaptation for users, along with their innate ability to handle delicate and smaller objects. Nevertheless, myoelectric prostheses are generally bulky and designed with more parts and heavier materials, making them a more expensive choice. They require a longer and more difficult training time due to their highly sensitive nature. While both power sources certainly have their advantages, they still demand improvement and advancements.

Future research should aim to develop hybrid models that integrate the strengths of both types, leveraging advanced control algorithms, improved sensor technologies, and personalized training programs to optimize prosthetic functionality and user satisfaction. Tailored rehabilitation programs focusing on skill development and motor learning can significantly improve the functional outcomes for users of both prosthetic types. Such innovations are essential to advancing the field of upper limb prosthetics, addressing the inherent limitations of current designs, and ultimately enhancing the quality of life for amputees by providing more effective, reliable, and user-friendly prosthetic solutions.

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