

A State-of-the-Art Survey on Myoelectric Prosthetic Arm Design and Recent Developments

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Abstract

Introduction: The human hand is essential for independence, and its replacement after loss poses a major challenge in medicine and engineering. Prosthetic devices have evolved from basic wooden limbs to advanced bio-integrated systems, with myoelectric prostheses marking a key milestone. These devices interpret muscle-generated electrical signals to control movement, restoring dexterity that closely mimics natural function. **Objective:** This study evaluates historical advancements in prosthetic arm design and investigates diverse sensor fusion and integration techniques to improve the prosthetic arm system. **Methodology:** This study considers and critically evaluates a vast literature in the field of prosthetic arm design and development. **Results and Conclusion:** It is observed that the high cost, limited availability, and restricted access of prosthetic arms, especially in developing countries, push towards the design of affordable prosthetic solutions. It has driven innovations such as three-dimensional (3D) printing and simplified biosignal processing in prosthetic arms. 3D printing enables rapid, low-cost customization, while streamlined myoelectric systems maintain essential functionality at reduced expense. Together, these technologies hold promise for improving accessibility and quality of life. Additionally, the advancements in machine learning could also improve the accuracy of prosthetic arm posture mimicking and classification. This review highlights the evolution, challenges, and future directions of low-cost myoelectric prosthetic arms, emphasizing the importance of affordability and inclusivity in advancing global prosthetic care.

Keywords

Prosthetic Arm, Muscle Activity, EMG Sensor, Machine Learning, Bio signal Processing.

1. Introduction

The human hand plays a vital role in maintaining independence, facilitating fine motor skills, communication, self-care, and occupational activities. Loss of an upper limb, whether caused by trauma, congenital deformities, or disease, represents a major physical, psychological, and social challenge for affected individuals. (Wilson P, et al., 2025) Globally, millions live with upper limb loss, with approximately 5,40,000 amputees in the United States of America alone and significantly higher numbers in developing nations such as India, primarily due to road accidents, industrial

injuries, and inadequate safety standards (Sreenivasan N, et al., 2018). However, available data points to around 5,000 new cases annually, with approximately 15,000 amputees having an unmet need for a prosthetic hand each year. (Nagaraja et al, 2016) The absence of a functional limb restricts independence, limits employability, and often leads to depression and social isolation, underscoring the urgent need for effective prosthetic rehabilitation.

Historically, prosthetic arms evolved from simple wooden or leather devices that offered only cosmetic or limited mechanical function, later progressing to cable-driven and body-powered models. (Vujaklija, et al., 2016) Although these early designs restored some functionality, they lacked natural control and often caused user discomfort. The introduction of myoelectric prosthetic technology marked a turning point, allowing electrical signals generated by residual muscles to control limb movement. (Kulkarni. and Uddanwadiker, 2015) This innovation significantly improved dexterity, user satisfaction, and reintegration into daily life. Despite their potential, the high cost and technological complexity of myoelectric prostheses continue to limit access, particularly in low- and middle-income regions. (Tadesse, 2015) Recent engineering advances such as three-dimensional printing, open-source actuator systems, and simplified bio-signal processing are driving the development of affordable alternatives. These innovations enable rapid customization, significant cost reduction, and broader global accessibility. (Sikder, et al. 2019) (Sanfilippo, et al.,2024) (Vishal, 2025).

This review study provides a comprehensive global perspective on how affordable myoelectric prosthetic arms influence amputees' quality of life while highlighting key challenges, innovations, and strategies to improve their accessibility and widespread adoption.

2. Methodology

A comprehensive literature search was undertaken, with inclusion criteria comprising peer-reviewed, English-language articles addressing technological advancements, affordability, accessibility, or quality-of-life outcomes related to upper-limb myoelectric prosthetic devices. Exclusion criteria included non-peer-reviewed publications, conference abstracts lacking full texts, and studies unrelated to upper-limb prosthetics. The search focused on studies related to myoelectric prosthetic arms published between 2000 and 2025. The databases searched included IEEE Xplore, Web of Science, Scopus, ScienceDirect, SpringerLink, and Google Scholar. The search keywords included "myoelectric prosthetic hand," "affordable prosthetic arm," "low-cost prosthetic design," "3D-printed prosthetic hand," and "quality of life in amputees." The initial search identified 112 articles. Titles and abstracts were screened to assess eligibility, followed by full-text reviews to confirm relevance and methodological quality. Fifty studies met the inclusion criteria and were selected for detailed analysis. The findings were narratively synthesized, emphasizing key themes including the evolution of prosthetic design, strategies for cost reduction, and the overall impact of affordable myoelectric technologies on user experience and quality of life.

3. Results and Discussion

The evolution of prosthetic technology has significantly transformed the rehabilitation and independence of upper-limb amputees. Early prostheses, primarily mechanical or body-powered devices, offered limited functionality and aesthetic appeal. The introduction of myoelectric prosthetic arms marked a paradigm shift, utilizing electromyographic (EMG) signals from residual muscles to control hand and wrist movements with enhanced precision and naturalness (Engdahl et al., 2015). These systems have been shown to improve dexterity, reduce physical strain, and enhance psychological well-being, thereby contributing substantially to users' quality of life (Resnik et al., 2020).

However, accessibility remains a major barrier, particularly in low- and middle-income countries (LMICs). The high cost of sensors, actuators, and control electronics often exceeding several thousand dollars renders advanced myoelectric devices unattainable for most amputees in resource limited contexts (Sengupta, and Lakshminarayanan). Studies highlight that while technological innovation in high income countries emphasizes performance and customization, research in LMICs focuses on cost reduction, modular design, and locally sourced materials to create affordable alternatives (Singh et al., 2022). Open source hardware platforms and 3D printing have emerged as promising strategies for low-cost fabrication and repair (Ten Kate et al., 2017).

Furthermore, cultural perceptions, lack of clinical infrastructure, and inadequate training among prosthetists hinder widespread adoption. Collaborative global initiatives, such as the WHO, Global Cooperation on Assistive Technology (GATE), advocate for inclusive design and equitable distribution of assistive technologies. Future directions

emphasize integrating AI-driven control, low-cost EMG sensors, and sustainable manufacturing methods to bridge the affordability gap without compromising functionality.

In conclusion, the pursuit of affordable myoelectric prosthetic arms represents not only a technological challenge but also a social imperative ensuring that advances in bionic innovation translate into tangible improvements in independence, dignity, and quality of life for amputees worldwide.

Fifty studies published between 2000 and 2025 met the inclusion criteria and were analyzed. The reviewed literature demonstrates substantial progress in myoelectric prosthetic arm technology, emphasizing affordability, functionality, and user centered design. Findings were synthesized across four major themes, i.e., technological advancements, cost reduction, user outcomes, and global accessibility, followed by a discussion of research gaps and future directions.

3.1. Technological Advancements and Design Evolution

Over the past two decades, myoelectric prosthetic arms have evolved from simple, single channel electromyographic (EMG) control systems to advanced, multi-channel, multi-degree-of-freedom designs incorporating pattern recognition and machine learning algorithms. Early devices, often bulky and limited in precision, have been replaced by lightweight, sensor-integrated systems capable of interpreting complex muscle activity to generate smoother and more intuitive movements (Abdikenov et al.,2025) (Ison and Artemiadis, 2014) (Nguyen.,2021) (Ortiz-Catalan, et al, 2012). Surface and intramuscular EMG signal detection techniques, both are widely used. However, surface EMG remains non-invasive and cost-effective, whereas implantable myoelectric sensors and Targeted Muscle Reinnervation (TMR) methods enhance signal selectivity and enable simultaneous, proportional control of multiple joints. Additionally, the integration of 3D printing and lightweight composite materials has facilitated customizable and ergonomic designs suited to diverse anatomical needs. These innovations not only improve comfort and aesthetics but also support scalable, patient-specific prosthetic fabrication (Farina et al., 2014) (Widehammar et al.,2018) (Kamavuako, 2014) (Scheme, and Englehart, 2011).

3.2. Cost Reduction and Affordability Strategies

Approximately one-third of the reviewed studies focused on cost reduction without compromising functionality. Open-source hardware platforms, 3D-printed components, and modular architectures emerged as key strategies to enhance affordability. Community-driven initiatives employing low-cost EMG sensors, Arduino-based control units, and printable prosthetic parts have demonstrated that effective devices can be produced at less than 10% of the cost of commercial systems (Cazon-Martin, et al., 2019) (Chen, Z,2023) (Zuniga, 2015). Frugal engineering initiatives from India and Africa highlight how local fabrication, digital manufacturing, and social entrepreneurship can overcome financial and logistical barriers. These approaches emphasize the use of locally available materials and decentralized production to ensure accessibility in low- and middle-income countries. However, challenges remain in ensuring durability, component standardization, and compliance with clinical and regulatory standards, which are crucial for long-term adoption and global scalability (Cordella, et al, 2016) (Silva, 2021).

3.3. Impact on User Outcomes and Quality of Life

Enhancing user independence and quality of life remains the central goal of prosthetic innovation. Studies consistently report that users of myoelectric prostheses experience improved dexterity, greater satisfaction in performing daily activities, and enhanced psychosocial well-being compared to those using body-powered devices (Biddiss, and Chau, 2021). The incorporation of proportional grip control and multi-channel EMG sensing has significantly improved performance in fine-motor tasks such as writing, grasping, and object manipulation (Chadwell, et al.,2016). Nonetheless, several barriers to long-term use persist. Device weight, limited battery life, high maintenance costs, and the need for extensive user training can lead to device abandonment, particularly in resource-limited settings. Training and rehabilitation programs are essential to help users adapt to advanced EMG control systems, especially those employing machine learning-based pattern recognition. Comparative studies have shown that low-cost, 3D-printed myoelectric arms can deliver acceptable performance and high user satisfaction when accompanied by appropriate rehabilitation support (Mohan, et al.,2022).

3.4. Accessibility and Global Research Trends

The geographical distribution of research indicates a global diversification of innovation. Historically, North America and Europe have led advancements in high-performance control systems and precision engineering. In recent years, emerging economies in Asia, Africa, and Latin America have contributed significantly to the field through frugal, context-specific solutions that prioritize affordability and local relevance (Bhaskaran et al.,2020). Initiatives in India,

have leveraged low-cost EMG modules and open-source designs to establish community-based fabrication labs and repair hubs. These efforts align with the global movement toward prosthetic democratization ensuring equitable access to assistive technologies. Despite such progress (Table 1), large-scale clinical validation and longitudinal outcome studies remain limited. The absence of standardized evaluation metrics further complicates cross-comparison between devices and regions (Dandekar, 2021) (Kuiken, et al., 2009).

Table 1. Overview of different approaches to prosthetic hand design

Design Method	Strengths	Weaknesses
Bio-Inspired Design	Enables lifelike motion and appearance by replicating natural hand biomechanics. Promotes a strong sense of embodiment and familiarity for users.	Involves complex bioengineering and mechanical replication. Limited adaptability to individual anatomical variations. Precision in fine motor control remains challenging.
3D Printing and Open-Source Design	Offers cost-effective, customizable, and rapidly prototyped prosthetics. Open-source platforms enhance accessibility and collaborative development.	May lack durability compared to conventional materials. Limited integration of high-tech features. Customization often requires advanced technical skills.
Neural Interface and Brain-Controlled Systems	Provides direct, intuitive control via neural signals. Enables seamless synchronization with user intent and high degrees of freedom in motion.	Requires complex signal acquisition, processing, and calibration. Invasive implantation and ongoing system maintenance are needed.
Exoskeleton-Assisted Design	Enhances grip strength, endurance, and dexterity. Useful for tasks involving lifting or heavy-load assistance.	Bulkier and less discreet than standalone prostheses. Synchronization between the exoskeleton and prosthetic hand can be difficult, requiring user training.
Anthropomorphic Design	Promotes aesthetic realism and social acceptance. Improves body image and psychological comfort through human-like form and motion.	High design complexity and fabrication cost. Realistic appearance may not equate to improved functional performance. May not suit users prioritizing utility over aesthetics.
Muscle-Driven Design	Uses natural muscle contractions for intuitive, proportional control. Supports multi-degree-of-freedom hand movements.	Dependent on consistent, strong muscle signals. Limited precision and range of fine motion. Requires user adaptation and training for effective use.
Modular and Customizable Design	Allows adaptability to diverse user preferences and anatomical variations. Components can be replaced, upgraded, or adjusted for comfort and performance.	Modular joints and connectors may increase failure points. Adds assembly complexity and potential cost escalation.
Haptic Feedback and Sensory Integration	Restores tactile sensation, enhancing object manipulation and environmental interaction. Provides better awareness of grip force and position.	Designing realistic, reliable sensory feedback is technologically demanding. Sensor integration increases system complexity and may cause sensory confusion.

Table 1. Overview of different approaches to prosthetic hand design (cont.)

Design Method	Strengths	Weaknesses
Soft Robotics Design	Mimics the flexibility and compliance of biological tissue. Offers safe, adaptive interaction and natural grasping ability.	Limited load-bearing capacity and durability. Control of soft actuators is complex and may lack precision for heavy tasks.
Hybrid Biomechanical Design	Integrates mechanical robustness with bio-inspired adaptability. Achieves a balance between realism, functionality, and strength.	Complex coordination of biological and mechanical subsystems. Maintaining equilibrium between aesthetics and performance is challenging. Advanced manufacturing is often required.
Nanotechnology and Advanced Materials	Delivers superior strength-to-weight ratio, responsiveness, and durability. Enables compact, lightweight, and high-performance prosthetics.	High production costs and material fabrication complexity. Requires specialized expertise and evaluation of biocompatibility and long-term effects.

3.5. Limitations and Research Gap

While technological progress is evident, existing studies reveal several limitations. Many investigations are constrained by small sample sizes, short follow-up periods, and controlled laboratory settings that do not reflect real-world challenges. Variability in electrode placement, calibration protocols, and performance measures limits reproducibility and meta-analysis. Additionally, there is a lack of standardized indices for assessing dexterity, fatigue, and psychosocial adaptation in myoelectric prosthetic hand users. Long-term durability data, especially for 3D-printed and open-source systems, remain scarce, hindering clinical translation and widespread implementation (Miller, et al., 2018) (Resnik, 2012).

3.6. Future Directions and Clinical Implications

Future development must integrate affordability, functionality, and sustainability through interdisciplinary collaboration. Advances in artificial intelligence, adaptive signal processing, and self-calibrating algorithms hold potential to make prostheses more responsive to individual muscle variability. Hybrid designs combining neural interfaces, haptic feedback, and 3D-printed modular structures may define the next generation of cost-effective prosthetic systems (Tzemanaki, 2018). Clinically, establishing regional manufacturing networks and local repair hubs can enhance device longevity and reduce abandonment rates. Policies promoting assistive technology inclusion within public healthcare frameworks are essential to ensure equitable access. International collaboration among academia, industry, and humanitarian organizations will be pivotal in accelerating the translation of affordable myoelectric technologies from experimental prototypes to clinically viable solutions (Sujana, et al., 2023) (Wilson, 2025).

3.7. Proposed Improvements

Future advancements should focus on enhancing affordability, functionality, and long-term usability of myoelectric prosthetic arms through interdisciplinary innovation. Integrating low-cost EMG sensors, 3D printing, and modular open-source designs can significantly reduce production expenses. Developing self-calibrating, AI-driven control systems will improve adaptability and ease of use. Establishing regional fabrication hubs, training centers, and standardized clinical evaluation frameworks can strengthen accessibility and sustainability. Global collaboration among researchers, manufacturers, and policymakers is essential to ensure equitable distribution and continuous improvement, ultimately empowering amputees with affordable, durable, and user-friendly prosthetic solutions that meaningfully enhance their quality of life (Salazar, et al., 2025).

4. Conclusion

This review highlights that technological innovation alone does not guarantee improved quality of life; affordability, training, and inclusivity are equally essential. The path forward lies in merging engineering excellence with social responsibility, creating prosthetic systems that are not only intelligent but also accessible to all who need them.

Achieving this vision will require a global commitment to open innovation, clinical validation, and user-centered design, ensuring that affordable myoelectric prosthetic arms truly enhance function, independence, and quality of life worldwide.

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