Narrative Review Article

Past, Current, and Future State of Prosthetic Arms

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ABSTRACT

The functional capability and independence of people with upper-limb amputation have been greatly enhanced in recent years by advances in prosthetic engineering, materials science, and neural interfacing technologies. This paper summarizes the history of prosthetic arm development, discusses current research, and addresses the key challenges that must be resolved to ensure their widespread adoption. Key design features for the hand, wrist, and arm are explored, with an emphasis on dexterity, degrees of freedom (DOF), structural strength, and user comfort. The evolution of motion control is discussed, and the transition from passive and body-powered control systems to myoelectric control and the emerging field of neural and brain-computer interfaces is outlined. While there has been significant progress, comfort, control reliability, limitations in sensory feedback, cost, and ethics remain key challenges. A range of solutions was discussed, including adaptive socket design, modular design, machine learning algorithms, and sensory feedback systems to improve usability and accessibility. The paper emphasizes the need for continued interdisciplinary research and development, as well as user-friendly design, to enhance the usability and comfort of prosthetic arms.

Keywords: Prosthetic arm; Prosthetic design; Motion control; Passive prosthetic; Body-powered; Myoelectric; Neural-controlled

INTRODUCTION

It was estimated that 2.3 million people were living with limb loss in the US, with 9.2% having undergone upper extremity amputations (1). Limb loss is a considerable physical and psychological trauma to individuals that may prevent them from performing their daily activities and social interactions (2). For those who have lost their limbs, prosthetics offer hope for regaining functionality and confidence.

Arm prosthetics are among the most sophisticated and rapidly advancing fields of biomedical engineering that not only simulate motion but also provide sensory feedback and fine motor control (3-4). Advanced prostheses can incorporate neural engineering and artificial intelligence (AI) technologies, enabling devices that can react to a user's thoughts or muscle signals more intuitively and precisely (5).

Despite significant progress, challenges remain in areas such as usability, comfort, durability, and affordability. Some of the most significant challenges are insufficient dexterity and grip strength, unnatural motion control, burdensome training demands, high maintenance and costs, and persistent abandonment rates (2, 6). Additionally, traditional prosthetics generally pay little attention to sensory feedback, despite its importance to the user's sense of their own body and their interactions

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Accepted August 3, 2026
https://doi.org/10.70251/HYJR2348.44702709

with the environment and other people (7).

This article provides an overview of the past and current state of prosthetic arm technology, its scientific foundations, ongoing challenges, and the potential future development directions, based on a narrative review of recently published articles. New frontiers in prosthetic arm research, such as direct neural control, advanced signal-processing algorithms, and tactile sensory feedback, are also briefly discussed to give the audience the latest view of the field.

An outline of the topics discussed in this article is shown in Figure 1. First, a high-level overview of the desired design features for the hand, wrist, and arm, plus recent advancements in the field, was provided. Then, common motor control strategies for prosthetic arms, including passive, body-powered, myoelectric, and emerging neural/brain control technologies, were reviewed. This was followed by a discussion on challenges that remain to be addressed and future directions for the development of prosthetic arms. The paper concluded with an appeal for further interdisciplinary collaboration to improve the functionality and affordability of prosthetic arms.

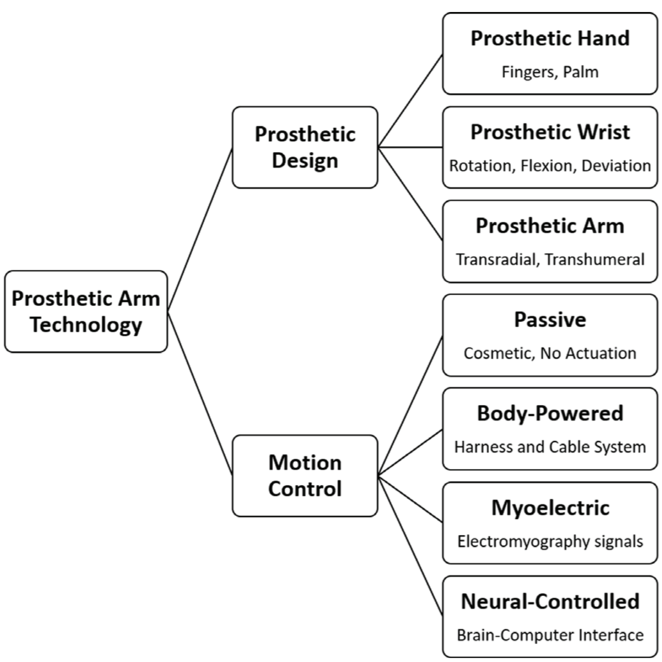

Figure 1. Outline of the main contents of this article. It starts with an overview of the main components of upper-limb prosthetics and their major design considerations, which is followed by a review of different motion control mechanisms.

PROSTHETIC DESIGN

One of the most crucial aspects of a prosthetic arm is its overall design, as it affects how useful and comfortable the arm will be for the user (8). The three components, i.e., hand, wrist, and arm, can be examined to understand a complete prosthetic system. The hand includes the fingers and palm, the wrist serves as the point of rotation and positioning, and the arm section encompasses the forearm and, in some cases, the upper arm.

Hand Design

The human hand is one of the most versatile and complex structures to replicate in designing a prosthetic device (4). It is composed of small bones and many tendons. The incorporation of actuators, sensors, and electronic components into a prosthesis that matches the size and weight of a natural hand (Figure 2a) is one of the primary challenges in prosthetic hand design (2-4). Additionally, to create a realistic hand model, each finger needs to move independently. This is a challenge as it requires complex mechanisms to be housed in a limited space. When designing a prosthetic hand, the main focus is to reproduce the functionality of human fingers and palm. Fingers are designed for grasping, holding, and manipulating objects, and some prosthetics provide

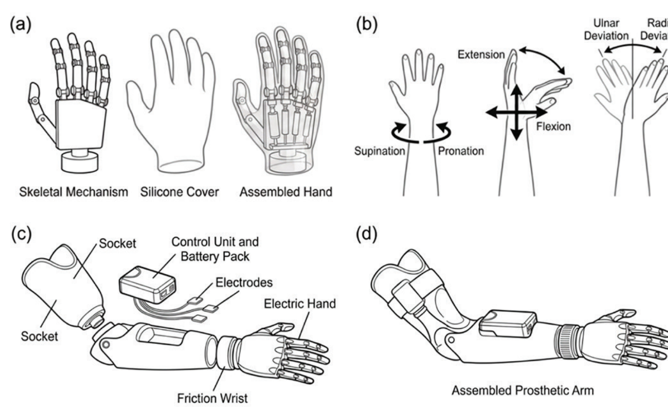

Figure 2. Illustration of prosthetic arm design. a) Schematic of a mechanical prosthetic hand with independently controlled fingers overlaid with a cosmetic silicone cover. b) Degrees of freedom of the human wrist include supination/pronation, extension/flexion, and ulnar/radial deviation. c) Sketch of a battery-run myoelectric upper limb with electrodes before assembly. d) A fully assembled prosthetic arm with mechanical hand, wrist, and an attached battery pack.

individual or grouped finger movement (4). Finger design in prosthetic hands focuses on replicating natural movement, strength, and dexterity. Fingers may be rigid, partially or fully actuated, allowing varying degrees of independent motion for tasks such as pinching, grasping, or typing. Advanced designs mimic humanlike bending and curling with tendon-driven mechanisms, motors, or soft robotics (4, 9). The materials chosen, such as lightweight plastics, carbon fiber, or silicone, influence flexibility, durability, and sensory feedback. Some prosthetic fingers are equipped with sensors that detect force or pressure, which allow users to adjust the grip for heavy or delicate objects (10).

The palm is the central structure of a prosthetic hand, connecting the fingers to the wrist and forearm, and provides stability and support for grasping and object handling. It should be strong and flexible enough for various types of grips, including small items and heavier loads (9, 11). Some palms use soft or padded materials to increase comfort and provide good pressure distribution (9). Advanced designs may include sensors to detect force or contact, allowing the user to adjust grip automatically for more precise task execution (11). The contour and shape of the palm can also affect how naturally the hand interacts with objects, impacting overall functionality and user comfort.

Wrist Design

The wrist is a very important part of the hand, contributing to its various movements, including rotation (supination and pronation), flexion and extension, and lateral side-to-side movement (Ulnar and Radial deviation) (Figure 2b). The mechanical design of the wrist device includes several areas of interest such as the number of degrees of freedom (DOF), kinematic architecture, and physical design parameters (12-13). Prosthetic wrists can be categorized by their DOF (1-DOF, 2-DOF, or 3-DOF models), each with its own benefits and drawbacks (13). Single-DOF prosthetic wrists allow movement in only one plane, usually either flexion/extension or pronation/supination. They are simpler, lighter, and more durable than multi-DOF options because they have only one motion. Their limited range of motion, however, can impact the user's natural hand position and reduce task versatility. Double-DOF prosthetic wrists provide two independent types of movement: usually flexion/extension and pronation/supination, allowing more natural positioning of the hand. This added functionality enhances the user's ability to make multiple wrist adjustments in complex or angled situations. The additional mechanical complexity can, however, make such wrists heavier, more costly, and energy-intensive than single-DOF wrists. Triple-DOF prosthetic wrists allow flexion/extension, pronation/supination, and radial/ulnar deviation. This multidirectional capability increases the range of movement of the user's hand, enhancing their dexterity when performing tasks requiring fine movements or unusual angles. The increased mechanical complexity comes at the expense of cost, weight, and maintenance frequency. Prosthetic wrists with 3-DOF are relatively uncommon, since most wrists have 1- or 2-DOFs actuated in serial configuration (12).

Arm Design

The design of the transradial (forearm) and, in some cases, transhumeral prosthetic (upper arm) (Figure 2c and 2d) is critical to the overall functionality, comfort, and control of the arm. The arm should have sufficient strength to withstand normal mechanical stresses of everyday use, but not be too heavy for extended use. This balance of strength and weight can be accomplished by using materials such as aluminum alloys, carbon fiber composites, and advanced polymers (14). The arm design also needs to be compatible with the user's residual limb for optimal load distribution and natural motion. The integration of sockets, alignment at joints, and suspension systems are designed to ensure maximum comfort and stability, reducing pressure points and skin irritation (8). Furthermore, mechanical and electronic components such as actuators, batteries, wiring, and control systems are housed in the arm and must be arranged efficiently to keep it compact and convenient. In more advanced prosthetic arms, the components are modular and can be modified or upgraded to make them more adaptable to the user's needs and better suit the various tasks they need to perform (15).

PROSTHETIC MOTION CONTROL

A major challenge in prosthetics is getting intuitive, reliable, and precise control of artificial limb movements (Figure 3) (2). Earlier passive prosthetic arms were operated by the opposite limb or manual mechanisms such as switches or buttons (16). Harnesses and cables are used to control body-powered prosthetic systems (17). Later improvements in biomedical engineering, however, allow myoelectric control, which detects and converts electromyography (EMG) signals from residual muscles to limb movement (15, 18). More recently, research has begun exploring direct neural-controlled and brain–computer interfaces, pushing the limits of how closely prosthetic arms can be integrated with the user's natural motor intention (19-20).

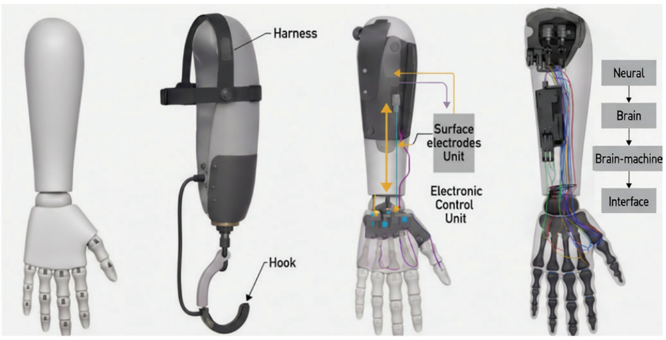

Figure 3. *Evolution of motion control mechanisms of prosthetic arms. a) An early version of passive cosmetic prosthetic arm. b) Body-powered prosthetic hand (hook) operated with a harness attached to the shoulder and cables. c) Myoelectric prosthetic uses residual muscle electrical signals captured by surface electrodes to operate the device. d) State-of-the-art neural-controlled prosthetic uses a brain-machine interface to convert cortical neuron signals to prosthetic movements directly.*

Passive Prosthetics

Earlier prosthetic arms were mainly passive devices made for aesthetic reasons with little to no mechanical components or functions. They are made of PVC, silicone, plastic, or steel, and can be customized to fit the amputee's residual limb. A passive prosthetic is typically operated by using the other hand (16).

Despite being viewed as a less functional replacement than active prostheses described in the following sections, approximately one-third of people with limb deficiency use a passive prosthesis (16). The reasons could be manyfold. First, passive hand prostheses can be more comfortable and appear more lifelike than active hand prostheses, and are considered a better choice by some users. Secondly, active prostheses are more challenging to train, control, and adapt. As a result, young children and recent amputees are sometimes prescribed a passive prosthetic hand, which is relatively easy to use (16). Lastly, passive prostheses are usually more affordable than active prostheses, an important consideration for many users, particularly in resource-constrained situations.

Body-Powered Prosthetics

Body-powered mechanisms were the most common type of early prosthetic arms, and they utilize cables, harnesses, and mechanical linkages to translate arm, chest, or shoulder movement into hand, wrist, or elbow motion (17). For instance, the user might flex the shoulder to pull a cable that opens a hand or extends the elbow. The systems were designed to be robust, lightweight, relatively easy to maintain, and readily accessible and reliable for everyday use (3). Modern manual prostheses can also include buttons, switches, or levers to activate specific functions, thereby increasing convenience and reducing effort for certain movements (2). However, the disadvantages of body-powered prosthetics are the constant manual effort required for operation and the less precise control, making them less suitable for fine motor functions such as holding small objects or performing delicate tasks. Furthermore, the range of motion is often limited by the mechanical design, and users need to master certain body movements to use the device effectively (2, 6). Although body-powered systems are still widely used, their reliance on mechanical input highlights the need for more intuitive control methods such as myoelectric and neural-controlled prosthetics to enable more natural, precise, and effortless movement.

Myoelectric Prosthetics

Myoelectric prosthetics are an important advancement over conventional manual operation systems, as they use EMG signals produced by the user's residual muscles to control the arm (15, 18). The signals are recorded using surface electrodes attached to the skin, amplified, processed, and converted into specific movements, such as hand opening and closing, wrist rotation, or elbow flexion/extension. The method allows more intuitive and natural control, since the prosthetic control is directly related to the user's intended muscle contractions rather than to the indirect body movements or mechanical input. In more modern designs, several sensors can be used, and sophisticated algorithms are employed to identify a variety of muscle patterns, resulting in more accurate and diverse movements (18). Despite these advantages, myoelectric prosthetics can be sensitive to factors such as muscle fatigue, skin impedance, sweating, and improper electrode placement, which lowers the signal accuracy. Furthermore, the devices often require training and periodic calibration for consistent performance and are heavier, more complex, and more costly than their body-powered counterparts (2, 6, 21). Nevertheless, the range of usable functions and dexterity of upper-limb prostheses have been significantly broadened with myoelectric control. In addition to surface-placed electrodes, implanted electrodes were also employed to enhance the robustness of myoelectric signal capture and control; however, they may not be attractive to everyone due to their invasiveness (3).

Neural-Controlled Prosthetics

Direct neural and brain control is the most advanced and promising method of prosthetic arm control, attempting to create a seamless bidirectional interface between the user's nervous system and the arm (19, 20, 22). This method uses high-resolution surface electrodes or implanted microelectrodes to record neural signals from peripheral nerves, the spinal cord, or specific regions of the cortex involved in motor intention (20). The signals are then fed to complex computer algorithms that convert them into precise multidimensional movements of the prosthetic hand, wrist, and elbow (Right side of Figure 4), allowing the person to approximate natural arm movement. In some systems, neural interfaces can also deliver sensory feedback from tactile sensors attached to an artificial body part, enabling the user to sense touch, pressure, or proprioception (Left side of Figure 4), thereby increasing dexterity and object manipulation (22, 23). Despite its potential, neural control faces substantial challenges, including the invasiveness of surgical implantation, the requirement for long-term signal stability, tissue compatibility, susceptibility to infection, and complex ethical questions regarding neural modification. Furthermore, such systems require extensive calibration, training, and maintenance for reliable operation. With ongoing progress in neuro-prosthetics, direct neural control is expected to transform the future of upper limb motion control, bringing unparalleled intuitive control, functional versatility, and integration with natural motor control and sensory processing (19-20).

Table 1 provides a high-level summary of the main benefits and disadvantages of the different types of motion control mechanisms used for prosthetic arms, namely: passive, body-powered, myoelectric, and neural-controlled prosthetics. Associated costs and typical uses are also listed. No single type is best for all situations, and the choice of prosthetic type is personal and depends on the user's needs, aesthetic versus mechanical preferences, and cost considerations, etc. (21).

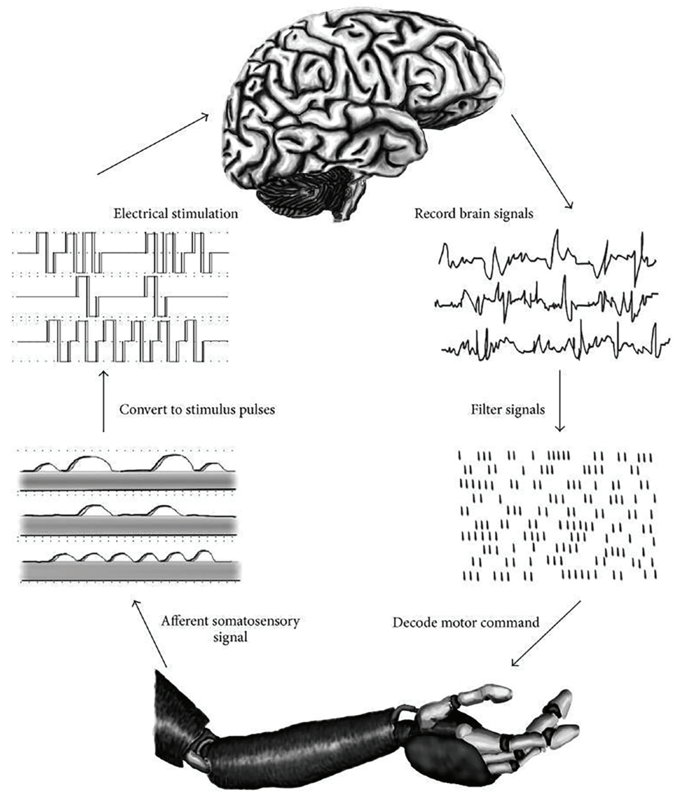

Figure 4. *Illustration of a neural-controlled prosthesis using direct brain-machine interface, sensory feedback, and advanced signal processing algorithms. Afferent somatosensory signal is taken from the prosthetic device (left side) and fed into the brain, from where the motor signal is sent back to the prosthetic limb (right side) (22). Adapted from Vidal GVW et al., Review of brain-machine interfaces used in neural prosthetics with new perspective on somatosensory feedback through method of signal breakdown. Scientifica. 2016;8956432. doi: 10.1155/2016/8956432. Licensed under CC BY.*

CHALLENGES WITH EXISTING PROSTHETICS AND POTENTIAL SOLUTIONS

Even though artificial arm technology has made great strides, several problems still affect the functional capabilities, durability, and applications of these devices. The challenges include mechanical design, control system, user comfort, durability, cost, accessibility, and ethical issues (2, 6). Addressing these issues is critical to increase the effectiveness of prosthetic arms and the overall quality of life of their users (2-3).

Comfort and long-term use are among the most

***Table 1**. Summary of major prosthetic arm motion control mechanisms, their advantages, limitations, and typical applications.*

Prosthetic Category	Motion Control Mechanism	Key Advantages	Primary Limitations	Costs	Typical Applications
Passive	Static	Lightweight, high comfort, durable, low maintenance and cost	Cosmetic with minimal functional utility	Lowest	Cosmetic, partial hand replacement
Body-Powered	Harnesses and cables	High reliability, durable, no battery needed	Cumbersome, uncomfortable, limited range of motion	Moderate	Coarse manual labor, sturdy utility tasks
Myoelectric	Surface EMG sensors	More natural control, High functional versatility	Heavy, battery dependent, sensitive to environmental factors, high maintenance	High	Daily life activities
Neural-Controlled	Implanted electrodes/neural interfaces	Intuitive control, potential for sensory feedback	Requires surgery, high complexity, ethical concerns, still at research stage	Very High	Advanced research, complex rehabilitation cases

important challenges when developing a prosthetic arm (2, 6). Weight, size, and appearance of the prosthesis are all important. Poor socket fit, non-uniform pressure distribution, and heat generated by the socket can cause skin irritation, pain, and tissue damage that may result in decreased use or even complete abandonment of the device (2, 6). The shape of the residual limb may change over time, due to muscle wasting or swelling, making it hard to maintain a consistent and comfortable fit. Potential solutions include the development of anatomically contoured sockets with moldable textile material and osseointegration (8). In the last few years, developments in 3D printing have enabled the production of much more customized sockets to fit individual anatomy (24).

Control reliability and intuitiveness also pose significant challenges. Passive and body-powered systems require physical effort and learned body movements, whereas myoelectric systems are sensitive to muscle fatigue, electrode placement, and environmental factors such as sweat. While promising, neural-controlled systems have issues of instability and surgical risk. Hybrid control methods that integrate different input modalities, machine-learning-based algorithms that learn over time to improve signal understanding, and better sensor technology that increase signal quality and robustness in real-world applications (3, 5, 21) are all potential solutions.

Another ongoing challenge is the lack of sensory feedback, which limits the user's ability to assess grip force, object texture, or hand position. Without sensory feedback, users rely mostly on visual input, which requires intense mental effort and makes tasks less efficient. Studies on sensory feedback systems, such as haptic or vibration feedback, and direct neural stimulation were conducted to explore the restoration of the sense of touch and proprioception. These methods have been effective in improving task performance and satisfaction, but they need further development in long-term reliability (3, 22, 23).

The cost and availability of the prosthetic arms are also important obstacles for their widespread use. High-tech prostheses with motors, sensors, and neural interfaces can be very costly, and not everyone can afford them. Financial expenses are also high due to maintenance and repair costs. Addressing this issue has involved creating modular prosthetic designs that enable upgrading specific parts of the system rather than replacing the entire system, or adopting low-cost manufacturing methods such as additive manufacturing and 3-D printing (9, 15, 25). Open-source prosthetic initiatives and scalable designs also hold potential for expanding global accessibility (3).

Last, but not least, ethical and psychological issues need to be discussed, especially with the advancement of neural-controlled prosthetics. Issues such as invasive procedures, data privacy, and user identity need to be addressed. Enabling users to be well-trained, adequately supported psychologically, and educated through a user-consent methodology is key to responsible implementation. Ethical guidelines and regulatory frameworks can aid in the development and implementation of emerging technologies in ways that prioritize user safety and autonomy (5, 20).

CONCLUSION

Prosthetic arm technology has made significant strides in biomedical engineering, neuroscience, and materials science, and the functionalities available to those with upper-limb loss have vastly improved. This paper presented the development of prosthetic arms in terms of mechanical design, control systems, existing limitations on performance and accessibility, and future development opportunities. The analysis of the different designs of the prosthetic hand, wrist, and arm highlights the ongoing need to balance dexterity, strength, weight, and durability; meanwhile, the progression of the control system from manual to myoelectric and neural-controlled systems reflects a clear shift toward more intuitive and natural ways for the user to interact with the device.

Despite these advances, there remain clear drawbacks, including discomfort, limited sensory feedback, high cost, and unreliable control. While advanced myoelectric and neural-controlled systems offer greater functionality, they also introduce challenges related to complexity, training requirements, long-term stability, and ethical concerns. Research on adaptive sockets, multi-DOF mechanisms, soft robots, machine-learning control, and sensory feedback technologies could lead to promising solutions to these problems and improve the user experience.

Looking ahead, the future of prosthetic arm development depends on interdisciplinary research and development as well as user-centered design. Ongoing close collaboration among engineers, clinicians, neuroscientists, and bioethicists will be key to developing prosthetic systems that are not only technologically powerful but also comfortable, affordable, and widely available. With ongoing technological advances, prosthetic arms have the potential to move beyond basic functional replacement and toward seamless integration with the human body, ultimately narrowing the gap between biological and artificial limb capabilities.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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