



## **Muscle-Controlled vs. Neuro-Controlled Prosthetic Hands: Technologies, Challenges, and Future Directions**

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### **Abstract**

### **Introduction**

The human hand plays an essential role in daily life, enabling people to perform a wide range of tasks, from basic self-care activities to complex actions such as writing. Hands also enable people to interact with and sense objects in their environment. Therefore, loss of hand function, whether caused by disease, injury, or amputation, can significantly impact an individual's quality of life, including independence in daily living and their ability to work. Advances in prosthetic technology have enabled artificial limbs to restore some, and in certain cases nearly all, of the functional capabilities of a natural hand. However, developing prosthetic devices that can replicate the natural movement and sense of a real human hand remains a major challenge.

A major challenge in prosthetic hand development is designing a control system that allows the users to control the prosthesis naturally and accurately. Traditional prosthetic devices often have limited functional degrees of freedom and restricted movement, and may require the user to use other parts of their body to control the device. To address this limitation, more advanced prostheses integrate advanced electronic motors, sensors, and operating systems to provide greater control of hand movements [1]. Various sensing systems have been developed to translate users' intended movements into prosthetic actions, including muscle-controlled and neuro-controlled prostheses.

Muscle-controlled prostheses, commonly known as myoelectric prostheses, use electrical signals produced by muscles to control movement. This system detects electrical signals from the user's surrounding muscles and processes them to determine the user's intended movements [2]. This approach enables voluntary control of the prostheses without requiring direct connection to the user's brain.

Brain-controlled interfaces, also known as neuro-controlled prostheses, capture brain transmissions and signals from the nervous system to determine the user's intended movements [3]. Instead of relying on sensing and decoding signals from residual muscles, neural interfaces can detect and translate neural signals into commands for the prosthetic device [4]. This approach provides direct but intuitive control of prostheses for the user to operate.

Although both muscle- and neuro-controlled prostheses offer the potential to improve the functionality of bionic limbs, specifically prosthetic hands, each approach has distinct advantages and limitations. Understanding these differences is essential for evaluating the current prosthetic technology and guiding future advancements. Therefore, this paper aims to compare muscle-controlled and neuro-controlled bionic hands by examining their control mechanisms, signal acquisition methods, functional degrees of freedom, sensory feedback

capabilities, technical requirements, and associated challenges. Through these comparisons, the paper will evaluate the strengths and limitations of each approach and discuss their potential to enhance users' independence and quality of life.

## Evolution of Prosthetic Controls

### *Traditional and body-powered prostheses*

Early prosthetic hands primarily focused on restoring the appearance of a missing hand, although some also provided some basic functional assistance. Traditional prostheses generally include passive (cosmetic) prostheses that replicate the natural appearance of the missing hand and body-powered prostheses, which use harness or cable systems that allow for a small degree of movement without any motors or batteries [5]. Users can use body movements, such as shrugging or moving the shoulder, to trigger the cable system and control the prosthesis, such as opening or closing an attached hook or mechanical hand [5].

Body-powered prostheses remain in use mainly because of their simple structure, durability, and lower maintenance cost. Traditional prosthetic hands are often constructed from durable metals, such as aluminum, steel, or titanium, and leather; the harness typically consists of leather or fabric straps that secure the prosthesis and transmit body movements to control its operations [5]. These materials are low-cost and generally easy to construct from. However, their effectiveness depends on the user's ability to generate movement and therefore operate the cable mechanism. Furthermore, these systems generally provide limited independent movement compared to the complex movements of a natural human hand. Since constant tension is required to generate movement, users often experience discomfort and physical exertion. These limitations led to the development of externally powered prostheses, which use electricity and more advanced control systems to generate movement [5].

### *Emergence of Myoelectric Control System (Muscle-Controlled Prostheses)*

The establishment of myoelectric control is a significant advancement in the prosthetic field because it allows the detection of electrical signals generated during muscle contraction, thus enabling users' movement control without the need for a harness [10]. Instead of relying on cable-transmitted force that triggers traditional body-powered prostheses, myoelectric prostheses detect electromyographic (EMG) signals associated with muscle contractions using tiny electrode sensors attached to users' skin (**Figure 1A**) [10]. These signals can then be electronically decoded and processed by a control system and translated into users' commands [6].

Myoelectric control provides an easier method for users to operate a prosthetic hand because movements can be initiated through intricate muscle activity rather than by pulling a mechanical harness alone. This eliminates users' discomfort and enables better control of the prostheses. Additionally, motorized hands can be coupled with the myoelectric control system to provide better precision, force, and intricate movements compared to harness-triggered hand movements. Currently, scientists have developed control algorithms that allow precise proportional control, on-off control, and pattern recognition to interpret muscle signals and operate more different movements [6].

Despite these advances, myoelectric prostheses still face challenges. Signal detection can be affected by muscle fatigue, electrode placement, changes in the skin-electrode interface, and many other factors [11]. Moreover, the number of reliable muscles available to control the prostheses may limit the overall effectiveness and ability of movements. Ultimately, there are many limitations for myoelectric control, varying from contact surface to signaling strategy. These challenges motivated researchers to investigate alternative approaches that allow the user's desired action to be executed more immediately and accurately.

### ***Emergence of Neural Interfaces (Neuro-Controlled Prostheses)***

Neural interfaces represent another major development in prosthetic control (**Figure 1B**). Rather than relying exclusively on muscle activity, these systems access signals directly from the nervous system and translate them into commands for prostheses [12]. Neural electrodes can be implanted into the motor cortex of the nervous system, where they can pick up neural signals transmitted in the brain when the users intend to move their hands [13]. Alternatively, these electrodes can be placed outside of the brain, either on the external surface of the skin (transcutaneous surface electrodes) or underneath the skin but outside of the brain (extranural electrodes), to detect neural signals [7].

Brain-computer interfaces, for example, record brain activity associated with intended movement and use computational algorithms to decode neural signals into control commands. Gilja et al. (2012) demonstrated that improvements in neural signal decoding algorithms could significantly improve the performance of brain-controlled prostheses [8]. Granted, this approach still faces challenges, including ensuring high precision and selectivity of signals and completely replicating natural hand movement and authentic dexterity.

### ***Limitations of Conventional Approaches and the Development of Next-Generation Prostheses***

The evolution from body-powered systems to myoelectric prostheses and neural interfaces reflects the continuing efforts in the field to advance the functionality and practicality of artificial limbs. Body-powered systems provide more affordable and relatively simple mechanical control, while myoelectric systems allow prosthetic movements to be initiated through muscle-generated electrical signals. Neural interfaces extend this approach by obtaining information from the nervous system.

However, not a single approach has addressed all the challenges of prosthetic control. Traditional body-powered devices have a limited freedom of movement and require physical effort, while myoelectric systems can be affected by signal variability and limitations in the number of independent control signals. Neural interfaces offer promising possibilities for more direct control and sensory feedback, but they pose additional technical challenges, including the need for reliable signal processing and long-term interface maintenance [8].

Conventional prostheses still face limitations in the freedom of movement, accuracy of control, and sensory feedback. These limitations have driven the development of future-generation prostheses aiming to improve control precision and replicate the natural functions of a human hand.

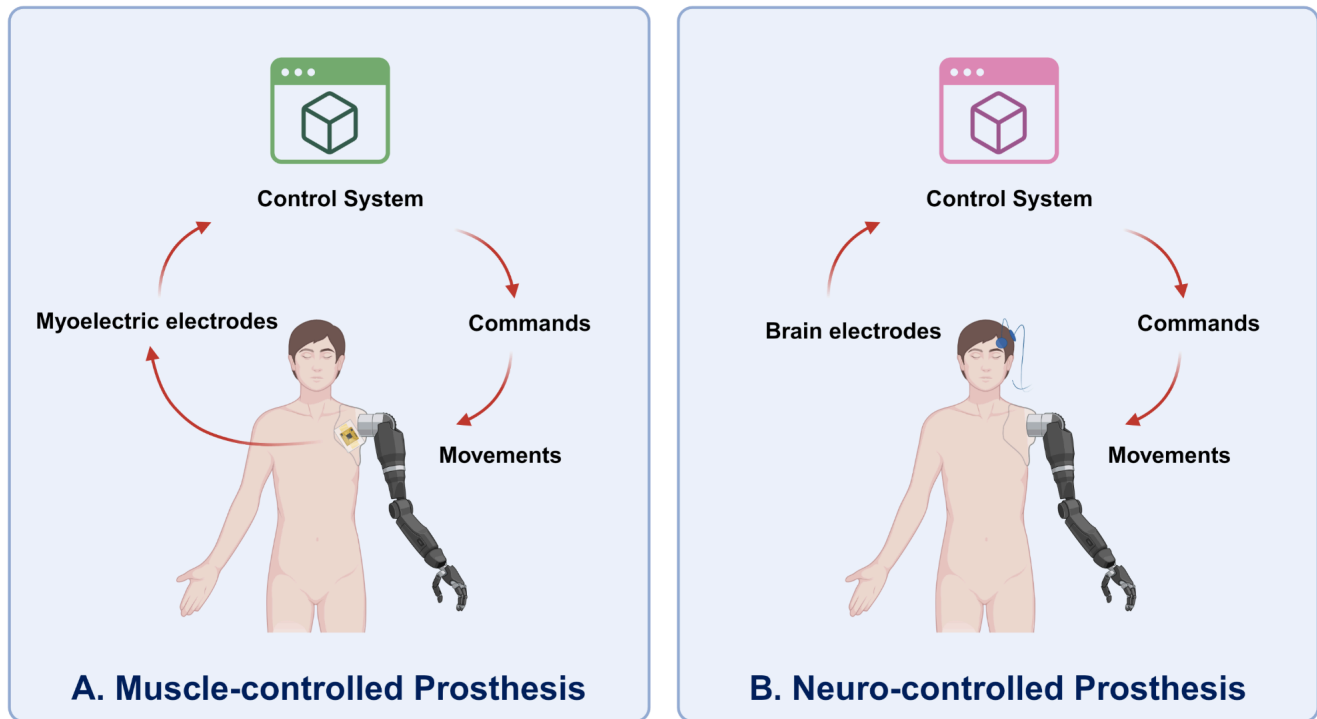


**Figure 1. Types of advanced prosthetic control systems. A. Muscle-controlled prosthesis:** Myoelectric electrodes pick up force signals from the residual muscles near the prosthetic attachment site. The control system translates these signals into intended movements and sends commands to the prosthetic hand. **B. Neuro-control prosthesis:** Electrodes on the skin surface of the brain or embedded inside the brain pick up EMG signals. Neural interfaces translate these signals into intended movements and send commands to the prosthetic hand.

## Muscle-Controlled Prostheses

### *Mechanism of Control*

Muscle-controlled prostheses, commonly known as myoelectric prostheses, use electrical signals generated by muscle contractions to operate artificial limbs. Myoelectric prostheses obtain signals by sensors, such as surface or implanted electrodes, and transmit them to the control system [2]. The system processes these signals and translates them into commands that activate the prosthesis's motors, enabling the device to perform the user's desired movements [2].

## ***Overview of Current Technologies***

Conventional muscle-controlled prostheses use several technologies to detect muscle activity. Surface electromyography (sEMG) uses electrodes placed on the user's skin to detect and measure electrical activity from the residual muscles on the skin surface [14]. Alternatively, implanted muscle sensors can detect muscle activity directly from within the body [6]. The detected signals are then processed by a control system and translated into commands that determine the user's intended movement.

Detected muscular signals, either from sEMG or implanted electrodes, can be processed using several approaches before they can be classified into intended movements. Pattern recognition control uses algorithms to identify patterns of muscle signals and then translate them into commands for different hand movements [6]. An alternative approach is called kinematographic control, which uses implanted magnetic tags to track changes in muscle position and movement information rather than using conventional electromyography (EMG) signals [9].

## ***Advantages***

One major advantage of muscle-controlled prostheses is that they allow users to control artificial hand movements through voluntary muscle contractions without direct connection to the human brain. sEMG systems are also relatively non-invasive because their signal electrodes are placed on the skin, eliminating the need for surgical implantation and making them easier to apply and maintain. Furthermore, advances in pattern recognition algorithms have improved the ability to interpret muscle signals and control hand movements.

## ***Limitations***

Despite these advantages, muscle-controlled prostheses still face several limitations. Muscle signals can vary because of fatigue, electrode displacement, and changes in skin contact, potentially reducing control accuracy [15]. Additionally, the freedom of movement of muscle-controlled prostheses depends on the number of available muscles [6]. Although advanced algorithms can improve control, replicating the natural coordination and sensory feedback of a natural human hand remains challenging.

## ***Neuro-Controlled Prostheses***

### ***Mechanism of Control***

Neuro-controlled prostheses use signals from the nervous system to determine the user's intended movements [8]. Depending on the interface, these signals can be received from the brain or nerves. Then, the system of the device would process the detected signals and translate them into commands that control the prosthetic hand [8]. Some neural technologies can also provide sensory feedback by stimulating nerves (reference). Though advanced algorithms can improve control, it is still challenging to replicate the natural coordination and sensory feedback of a human hand.

## ***Types of Neural Interfaces***

One major type is the brain-computer interface (BCI) [4]. This approach records brain activity associated with intended movements and converts it into control commands as mentioned above [4]. These devices may require implanted electrodes to obtain neural signals directly from the brain. Another type involves peripheral nerve interfaces, which interact with nerves outside of the brain to access motor control and provide sensory feedback [7].

## ***Advantages***

A major advantage of neuro-controlled prostheses is their potential to provide more direct and immediate control of the prostheses, particularly when conventional muscle signals are insufficient. By translating neural activity, these systems may provide a higher variety, complexity, and freedom of movement [7]. Certain neural interfaces can provide sensory feedback by stimulating the nervous system, helping users to retain the touch of objects [17]. These capabilities are significant towards restoring more natural hand functions.

## ***Limitations***

Despite their advanced approach, neuro-controlled prostheses face significant technical and clinical challenges. Invasive neural interfaces have many risks associated with the surgery required for neural implants [16]. Neural signals can also be difficult to decode consistently, and implanted systems must maintain sustainable and reliable performance over a long period of time (reference). Also, the maintenance of implants requires significantly more effort and money compared to less advanced electrodes, such as sEMG [18]. Moreover, the equipment and processing systems are very complex to innovate and develop. Therefore, although neural interfaces offer promising possibilities, further development is needed to improve their reliability, practicality, affordability, and ability to replicate natural hand movement and sensation.

## ***Discussion***

Muscle-controlled and neuro-controlled prostheses differ primarily in the source of signals used to operate the device. Muscle-controlled systems rely on muscle activity at the prosthetic connection site and nearby muscles, whereas neuro-controlled systems can access signals from the brain or peripheral nerves. These differences influence their invasiveness, complexity, and future potential to mimic a natural human hand.

In terms of practicality, muscle-controlled prostheses using surface electrodes require less invasive procedures, so they may be preferable to implement. Neuro-controlled prostheses may offer more direct, accurate control with sensory feedback, but implanting interfaces may require additional surgical, technical, and economic challenges. The signal-associated performance of prostheses using both approaches varies, depending on the degree of development of the technology. However, despite the challenges in implementation, neuro-controlled prostheses provide slightly better signal detection compared to muscle-controlled prostheses.

Another important factor is the functional degree of freedom, which refers to the number of independent movements a prosthetic hand can perform. Both approaches demonstrate multiple movements, but their effectiveness may depend on the user's condition and quality of



prostheses. Therefore, neither approach is universally superior. Muscle-controlled systems offer practical advantages, while neuro-controlled systems provide advanced control and high future potential.

## **Conclusion**

Muscle-controlled and neuro-controlled prostheses represent two important approaches to the improvement of bionic hands. Muscle-controlled systems provide practical means of translating muscle activity into movement, whereas neuro-controlled systems offer the potential for more direct control and sensory feedback. Despite their respective limitations, future developments in signal processing and neural interface technology would help evolve prostheses that could more closely replicate the movement, dexterity, and sensation of a natural human hand.

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