Proceedings of ICMMGH 2026 Symposium: Cell and Molecular Biology: Understanding Immune Cell Functions
DOI: 10.54254/2753-8818/2026.PJ31776

The Advances, Challenges and Prospects of Bionic Limbs

Shihao Liu

INTO Manchester, Manchester, United Kingdom
2932097142lsh@gmail.com

Abstract. This paper provides a concise overview of bionic limb development and their potential future directions. It traces the evolution from early mechanical prostheses to modern intelligent and neuro-integrated systems. The discussion focuses on recent progress in key areas, including sensory feedback reconstruction, neural–muscular interface–based intuitive control, high-density EMG signal decoding, and multi–degree-of-freedom motion control supported by AI. It also examines major challenges hindering clinical translation, such as unstable biological signal acquisition, long-term biocompatibility of implanted neural interfaces, and high cost and limited accessibility. Finally, it discusses prospective development in areas like medical rehabilitation and human–machine integration, suggesting that neural interfaces and intelligent control algorithms will promote greater naturalness, personalization, and functional stability in future systems.

Keywords: Biomimetic limbs, Neural interface, EMG control, Sensory feedback, Artificial Intelligence

1. Introduction

Biomimetic limbs, as high-tech prosthetic devices that mimic the functions and behaviors of biological systems, represent the most advanced stage of prosthetic development and can be understood as highly mechatronic and intelligent systems. Therefore, this paper begins with a brief review of the history of prosthetics, followed by an examination of the transition from traditional prosthetic limbs to modern bionic limbs, and finally discusses the future development trends and challenges of this field.

Early prosthetics date to ancient Rome, where archaeological findings indicate the use of simple wooden or metal structures. The Industrial Revolution later had a significant influence on prosthetics, transforming them from craft-based products made by blacksmiths or carpenters into more specialized and standardized devices [1]. After major wars, governments tended to increase investment and research into prosthetic technologies; for example, the American Civil War, World War I, and World War II all greatly accelerated the development of stronger and lighter prosthetic materials [2].

In 1945, Reinhold Reiters filed one of the earliest patents related to myoelectric control of artificial hands, marking an important milestone. However, early prototypes relying on vacuum tube technology required substantial power and offered poor efficiency, limiting their everyday usability

[3]. In the 1980s, Alexander Kobrinski developed the first clinically significant myoelectric prosthesis [4].

With the emergence of transistors, processors, and computer-aided design and manufacturing (CAD-CAM), the prosthetic industry experienced further modernization. Digital solutions began appearing in upper-limb prosthetics, improving production efficiency and device consistency [2]. By the 1980s, myoelectric prostheses were widely used in rehabilitation centers and have since become a common choice for amputees.Compared with body-powered devices, they offer better comfort and aesthetics, despite persistent challenges like signal instability and high cost [4]. This integration of bionics and intelligence laid the groundwork for subsequent advancements

2. Current achievements and technologies of bionic limbs

2.1. Sensory feedback

The development of bionic limbs seeks to restore both motor function and natural sensory feedback. The absence of tactile input forces reliance on visual monitoring, impairing control precision and body ownership [5]. Thus, reconstructing sensory feedback is crucial for enhancing bionic limb practicality and user experience.

Non-invasive technologies for transmitting sensory feedback through bionic hands were first introduced in the 1970s. They can be categorized into electrical and mechanical stimulation based on the nature of the stimulation strategy, and typically provide pressure, vibration, and other feedback modes.

Although these technologies can provide limited feedback, they struggle to replicate real tactile sensations [6]. The development of peripheral nerve electrical stimulation technology has enabled researchers to directly activate the residual nerves of amputees through implanted electrodes, reconstructing tactile localization sensation. Researchers such as Raspopovic reported in Science Translational Medicine that subjects stimulated on the median/ulnar nerves of their forearm stumps could accurately identify the stimulation locations of different fingers while their eyes were closed [7].

Further work, such as Flesher et al.'s use of intracortical microstimulation (ICMS), has induced natural tactile sensations at the cortical level, achieving closed-loop sensory feedback [8]. Recent advances in multimodal systems now allow bionic hands to convey complex information like pressure, temperature, and texture simultaneously.

The neural-osseous integration system proposed by Ortiz-Catalan et al. has achieved the first long-term stable use of sensory feedback prostheses in daily life [9]. Meanwhile, Silvestro Micera and others have developed the MiniTouch system, which helps upper limb amputees restore natural temperature sensation through non-invasive means by altering the temperature of specific areas of the residual arm [10]. These studies mark the gradual transition of bionic sensory systems from the experimental verification stage to clinical application.

However, the biocompatibility, signal stability, and naturalization of the tactile sensation of long-term implanted electrodes remain important challenges for future research. With the combination of high-resolution neural interfaces, flexible materials, and artificial intelligence signal decoding technology, the sensory feedback of bionic limbs will gradually approach the real experience of human hands.

2.2. More intuitive control

Intuitive control aims to align prosthetic motion with natural motor intention. In recent years, "intuitive control" reconstruction for amputees, Targeted Muscle Reinnervation (TMR), and Regenerative Peripheral Nerve Interface (RPNI) have gradually become mature neurosurgical reconstruction methods. The core principle of both is to surgically connect the stump motor nerves to new muscle tissues, allowing the motor commands issued by the brain to be transmitted to the new muscle source and subsequently recognized by bionic prostheses as multi-degree-of-freedom control signals [11].

Meanwhile, interfacing with the peripheral nervous system for feedback also helps reduce postoperative neuromas and phantom limb pain [6]. The current trend combines high-density EMG electrodes with AI decoding to enhance signal resolution and the natural mapping of motor intentions, fostering more intuitive control. At the software level, researchers are optimizing the signal decoding process through deep learning, adaptive control, and collaborative modeling, converting complex neural-electromyographic signals into stable and continuous action outputs in real time [12]; meanwhile, the introduction of closed-loop control algorithms and multimodal sensory feedback systems enables bionic prostheses to dynamically adjust based on environmental changes and user's motion state, achieving more autonomous and intelligent control closer to natural limbs [13,14].

2.3. Multi-degree-of-freedom control

Traditional electromyography (EMG)-based prosthetics are limited by open-loop control and single-signal analysis, enabling only basic grasping actions and lacking natural, multi-degree-of-freedom (DoF) coordinated movements. To achieve more precise control, recent research has increasingly focused on pattern-recognition methods based on multi-channel EMG signals. In this approach, EMG data are synchronously collected through an electrode array placed on the residual limb. EMG data are collected and classified into motion commands. Classifiers such as linear discriminant analysis and support vector machines are then used to decode specific muscle-activation patterns into complex motion commands intended by the user, such as pointing or gesture expression [15].

However, robustness in real-world use remains challenging due to electrode drift, muscle fatigue, and limb position changes, which degrade EMG recognition accuracy [16]. Adaptive algorithms mitigate this by enabling online model updates to adjust to signal variations. Looking forward, integrating advanced algorithms such as deep learning to enhance classification performance, together with multimodal sensing sources—particularly inertial measurement units (IMUs)—is considered a key direction for achieving intuitive and reliable multi-DoF bionic control [15,17].

3. Challenges of bionic limb technology

3.1. Technical limitations

Despite numerous advancements in bionic limbs in the laboratory, the challenges and bottlenecks they face persist. In terms of sensory feedback, current bionic limbs still lag significantly behind natural limbs. The prevailing research focuses on two approaches: mechanical tactile feedback and neural electrical stimulation feedback. The former delivers tactile signals on the skin surface through vibration motors or pressure modules, which are simple in structure but limited in resolution. For instance, products such as Ottobock and Open Bionics on the market still primarily rely on visual feedback, failing to enable users to truly "feel" the limbs, which may lead to low psychological identification and rejection of the product. The latter directly activates sensory nerves through implanted neural stimulation electrodes, achieving a more natural perception experience. However, it still encounters issues such as difficulty in controlling stimulation precision, signal delay, and long-term electrode stability [18].

The introduction of neural interface technology currently offers a new direction for developing high-quality feedback systems in the future; however, it is currently in the experimental stage and has not yet achieved high precision, multi-channel, and long-term stable signal transmission [19].

Secondly, the stability of biological signal acquisition and control is also a core challenge. Most existing bionic limbs rely on surface electromyography signals or implantable neural interfaces to decode user intentions [20]; however, such signals are highly susceptible to electrode drift, skin impedance changes, and muscle fatigue, resulting in reduced recognition accuracy and control delays. In recent years, the introduction of high-density electrode arrays and adaptive algorithms has improved the robustness of signals; however, maintaining their stability in long-term wear and complex dynamic environments remains challenging.

Additionally, the biocompatibility and long-term reliability of neural interfaces remain crucial issues that urgently require attention. Technologies such as targeted muscle reinnervation (TMR) and regenerative peripheral nerve interface (RPNI) can evidently achieve a more natural transmission of motor intentions and tactile feedback [19]; however, implantable electrodes often face issues such as signal attenuation, inflammatory reactions, and tissue encapsulation, which can affect long-term use [18]. To improve biocompatibility, researchers are exploring the application of flexible materials, conductive polymers, and degradable microelectrodes; however, these solutions still require further development to mature for clinical use.

Lastly, the practical application of bionic limbs is also limited by power and structural design considerations. Current-powered prosthetics rely on batteries and servo systems, making it challenging to optimize their endurance, weight, and output efficiency simultaneously [21]. Energy recovery and flexible drive mechanisms are emerging trends but have not yet been widely adopted. Overall, bionic limb development is transitioning from "experimental verification" to "daily usability". Core challenges in realism, stability, durability, and energy optimization are expected to be addressed through future advances in materials, algorithms, and processes [22].

3.2. Ethical and social implications of bionic limb technology

Beyond technical hurdles, bionic limb adoption raises profound ethical and social issues. Unlike traditional prosthetics focused on repair, advanced bionic systems can enhance users' abilities, blurring the line between restoration and augmentation. This has led to a blurring of the boundaries between "repair" and "enhancement". With the improvement in the performance of powered prosthetics, intelligent exoskeletons, and brain-controlled systems, some bionic devices in the experimental stage have surpassed the functions of natural limbs, sparking ethical debates on "human enhancement". If prosthetics are not only used to compensate for disabilities but also endow users with extraordinary abilities, it will inevitably redefine the concepts of "fair competition" and "disability". Enhancement technologies raise ethical concerns regarding identity and fairness [23].

Secondly, data privacy and neural rights have emerged as new focuses. High-intelligence prosthetics require the collection and analysis of users' physiological and neural signals. Yet, there are still no professional standards for the security, usage rights, and privacy protection of this data. Some scholars have proposed the concept of "neural rights", advocating for the inclusion of neural data protection within the framework of human rights and its integration into the constitution to prevent the abuse and surveillance of human rights [24]. This may be incorporated into the legal system and possibly legislated in the future.

Meanwhile, psychological and social adaptation issues are also a crucial aspect that cannot be overlooked. When bionic technology deeply intervenes in the human body, it may alter individuals' perception of "bodily integrity". Advanced prosthetics not only enhance the autonomy and social participation of people with disabilities, but also, some users may experience psychological issues such as body alienation or technological dependency after long-term reliance on high-tech devices. Therefore, promoting bionic technology, psychological counselling and social acceptance cannot be overlooked. Overall, ethical and social scrutiny not only determines whether technology can be accepted but also determines whether it can be integrated into human life in a fair, dignified, and safe manner. This also indicates that for bionic limbs to truly achieve widespread application based on technologies such as brain-computer interfaces, there is still a long way to go.

3.3. The cost and availability of bionic limbs

While technology continues to advance, the issues of price and accessibility of bionic limbs remain severe. Currently, traditional robotic prosthetics cost between $5,000 and $50,000. In contrast, 3D printing can produce functional prosthetics typically used for basic grasping functions at a cost ranging from $50 to $500, depending on the design complexity and materials used. However, long-term maintenance, training, and control algorithm iteration still incur hidden costs, making them unaffordable for most ordinary patients and limiting their penetration in the medical system.

Furthermore, there exists significant inequality in accessing prosthetics globally. Users in developed countries can obtain high-end prosthetics through military funding or commercial insurance, whereas mechanical prosthetics remain the mainstay in developing countries. The World Health Organization notes that only approximately 10% of people with residual limbs worldwide have access to suitable prosthetic services. This technological gap hinders the development of bionic limbs from benefiting a broader population.

Furthermore, inadequate policy and insurance support hinder accessibility, as many countries exclude high-end bionic prosthetics from reimbursement, leaving。 users to bear the full cost. In addition, some open-source organizations (such as e-NABLE and Open Bionics) are attempting to provide low-cost solutions through 3D printing and modular design, which can also significantly reduce the manufacturing cycle of prosthetics [25]. However, their scale is limited, making it challenging to meet clinical needs and benefit a broader range of people.

4. Conclusion

Bionic limb development exemplifies the deep integration of engineering, neuroscience, and material science. Breakthroughs in bidirectional neural interfaces, haptic/multimodal feedback, and AI-driven adaptive control have brought their function closer to natural limbs.

In the future, the integration of brain-computer interfaces, AI learning algorithms, and flexible bionic materials will become the core driving force for the continuous advancement of bionic limbs. These technologies will not only enable more natural motion control and realistic tactile feedback but also enhance the overall user experience. They will also expand the application scenarios of bionic limbs beyond medical rehabilitation, including industrial production, disaster relief, military applications, and space exploration.

Simultaneously, the widespread adoption of bionic limbs will also spark ethical discussions about the boundaries between "restoration" and "enhancement," which will involve social issues such as data privacy, neural rights, and technological accessibility.

In summary, the future of bionic limbs is no longer confined to replacing lost limbs. Instead, it marks a new stage of expanding human capabilities and reshaping the relationship between humans and machines. Through interdisciplinary collaboration and technological advancements, bionic limbs are poised to become a significant milestone in the deep integration of humans and intelligent technology.

References

[1] Shen, L., & Yu, H. (2012). The development history of prosthetics at home and abroad. Tissue Engineering Research, 16(13), 2451

[2] Raschke, S. U. (2022). Limb prostheses: Industry 1.0 to 4.0: Perspectives on technological advances in prosthetic care. Frontiers in Rehabilitation Sciences, 3, 854404. https: //doi.org/10.3389/fresc.2022.854404

[3] McLean, L., & Scott, R. N. (2004). The early history of myoelectric control of prosthetic limbs (1945–1970). In Powered upper limb prostheses: Control, implementation and clinical application (pp. 1–15). Springer. https: //doi.org/10.1007/978-3-662-05063-4_1

[4] Zuo, K. J., & Olson, J. L. (2014). The evolution of functional hand replacement: From iron prostheses to hand transplantation. Plastic Surgery, 22(1), 44–51. https: //doi.org/10.1177/229255031402200111

[5] Bensmaia, S. J., Tyler, D. J., & Micera, S. (2023). Restoration of sensory information via bionic hands. Nature biomedical engineering, 7(4), 443–455. https: //doi.org/10.1038/s41551-020-00630-8

[6] Raspopovic, S., et al. (2014). Restoring natural sensory feedback in real-time bidirectional hand prostheses. Science Translational Medicine, 6(222), 222ra19.

[7] Flesher, S. N., et al. (2016). Intracortical microstimulation of human somatosensory cortex. Science Translational Medicine, 8(361), 361ra141.

[8] Ortiz-Catalan, M., et al. (2023). A highly integrated bionic hand with neural control and feedback for use in daily life. Science Robotics, 8(81), eadd6122.

[9] Micera, S., & Shokur, S. (2024). Our research path toward the restoration of natural sensations in hand prostheses. Artificial Organs, 48(9), 937–942. https: //doi.org/10.1111/aor.14823

[10] Kuiken, T. A., Li, G., Lock, B. A., Lipschutz, R. D., Miller, L. A., Stubblefield, K. A., & Englehart, K. B. (2009). Targeted muscle reinnervation for real-time myoelectric control of multifunction artificial arms. JAMA, 301(6), 619–628. https: //doi.org/10.1001/jama.2009.116

[11] Song H, Herr H M, Clites T R, et al. Continuous neural control of a bionic limb restores biomimetic gait after amputation [J]. Nature Medicine, 2024, 30(7): 1270-1280. DOI: 10.1038/s41591-024-02994-9.

[12] Sensinger, J. W., & Clark, G. A. (2015). The effect of haptic feedback on closed-loop control of a myoelectric prosthesis. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 23*(4), 596–606. https: //doi.org/10.1109/TNSRE.2014.2343381

[13] Markovic, M., et al. (2015). The role of feedback and feedforward control in myoelectric grasping. Journal of NeuroEngineering and Rehabilitation, 12(1), 103. https: //doi.org/10.1186/s12984-015-0092-7

[14] Cimolato, A., et al. (2022). EMG-driven control in lower limb prostheses: A topic-based systematic review. Journal of NeuroEngineering and Rehabilitation, 19(1), 43. https: //doi.org/10.1186/s12984-022-01019-1

[15] Jiang, N., Muceli, S., Graimann, B., & Farina, D. (2023). Multimodal integration for improving the robustness of myoelectric control: A review. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 31(4), 1452–1465. https: //doi.org/10.1109/TNSRE.2023.3257895

[16] Bellmann, M., Schmalz, T., & Blumentritt, S. (2017). Crossover study of amputee stair ascent and descent biomechanics using Genium and C-Leg prostheses. Journal of NeuroEngineering and Rehabilitation, 14(1), 41. https: //doi.org/10.1186/s12984-017-0256-1

[17] Kanoga, S., Osu, R., & Morimoto, J. (2015). Covariate shift adaptation in EMG pattern recognition for prosthetic device control. IEEE Transactions on Biomedical Engineering, 62(11), 2750–2760. https: //doi.org/10.1109/TBME.2015.2445753

[18] Díaz, D. D., del Valle, R. C., Navarro, J., Olsson, R., & Micera, S. (2019). Long-term functionality of transversal intraneural electrodes is improved by dexamethasone treatment. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 27, 457-464. https: //doi.org/10.1109/TNSRE.2019.2897256"

[19] Vu, P. P., et al. (2020). A regenerative peripheral nerve interface for prosthetic control. Science Translational Medicine, 12(533), eaay2857. https: //doi.org/10.1126/scitranslmed.aay2857

[20] Zhang, F., Huang, H., & Liu, M. (2015). Intuitive control of a powered prosthetic leg during ambulation: A randomized clinical trial. Journal of NeuroEngineering and Rehabilitation, 12(1), 65. https: //doi.org/10.1186/s12984-015-0059-9

[21] Zhao, Z., Li, X., Wang, Y., & Zhang, L. (2023). Energy-efficient control strategies for powered prostheses. Journal of NeuroEngineering and Rehabilitation, 20(1), 45. https: //doi.org/10.1186/s12984-023-01125-8

[22] Cain, S. M., Gordon, K. E., & Ferris, D. P. (2018). Use of a powered ankle–foot prosthesis reduces the metabolic cost of uphill walking and improves leg work symmetry in people with transtibial amputations. Journal of the Royal Society Interface, 15(144), 20180442. https: //doi.org/10.1098/rsif.2018.0442

[23] Di Stefano, N., Jarrassé, N. & Valera, L. The Ethics of Supernumerary Robotic Limbs. An Enactivist Approach. Sci Eng Ethics 28, 57 (2022). https: //doi.org/10.1007/s11948-022-00405-1

[24] Hertz, N. Neurorights – Do we Need New Human Rights? A Reconsideration of the Right to Freedom of Thought. Neuroethics 16, 5 (2023). https: //doi.org/10.1007/s12152-022-09511-0

[25] McDonald, J. The advancement of prosthetic limbs in the 20th century. J. Rehabil. Res. Dev. 2010, 47, 389–405