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The application of biomimetic limbs in postoperative rehabilitation of amputees

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Abstract. Due to the inability to provide recovery opportunities, amputation is generally considered a failure of treatment. Traditional prostheses cannot interact with the surrounding environment, and the contact surface between the prosthesis and the residual limb is prone to wear and tear, causing pain to patients. Therefore, prostheses are generally regarded by patients as tools rather than a part of the body. In recent years, with the continuous development of artificial intelligence, materials science, and biomedical engineering technology, bionic limb technology has received widespread attention and application. Currently, bone integration and electromyography interface technology are widely applied in bionic limbs, allowing for more realistic and diverse options for prostheses for patients. Material innovation and machine learning technology can improve the mechanical performance, perceptual feedback effects, and autonomous learning ability of bionic limbs, but further research and exploration are still needed. This review paper aims to summarize and evaluate the current development status, application areas, and future research directions of bionic limb technology.

Keywords: bionic limbs, osseointegration, myoelectric interface, brain-computer interface.

1. Introduction

Amputation can have a significant impact on patients, causing not only secondary diseases in the residual limb but also psychological disorders due to changes in appearance and loss of basic abilities. Clinical experience shows that if a prosthesis fails to meet patients' expectations for appearance, function, and subjective considerations, it will eventually be rejected by the patient [1]. Although traditional prostheses can achieve multi-degree-of-freedom motion, users rely mainly on visual and pressure feedback from the socket at the interface between the residual limb and the prosthesis because of the lack of sensors, and they cannot alleviate phantom limb pain in some patients. The control of non-disabled limbs mainly relies on the transmission of limb movement and sensory feedback signals conveyed by neural fibers that dominate muscles, joints, tendons, and skin [2]. However, bionic limbs, through technologies such as myoelectric interfaces, brain-machine interfaces, and intelligent sensors, enable sensory feedback to be transmitted to the brain, making patients feel more realistic and natural.

2. Bionic limbs

Bionic prosthetic technology is an artificial limb technology that mimics the natural structure and function of limbs, utilizing advanced biomedical engineering, materials science, and artificial

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intelligence techniques. The aim of this technology is to help people with missing limbs regain movement and sensation and improve their quality of life and work.

Bionic prostheses typically include sensors and actuators to simulate biological sensing and motion capabilities. Sensors can receive external stimuli and convert them into electrical signals by measuring pressure or temperature to simulate touch or temperature sensation. Actuators can then convert these signals into mechanical motion, such as by using electric motors or hydraulic systems to simulate muscle contraction and relaxation.

Bionic prosthetic technology can achieve limb motion control and sensory feedback through various means, such as myoelectric interfaces, neural implants, visual feedback, and material innovation. Among these, myoelectric interface technology is the most widely used bionic limb control technology, which can convert limb motion into electrical signals through muscle electrical signal sensors and achieve precise limb control and motion sensory feedback. Neural implant technology can achieve more natural limb motion and sensory feedback, but requires highly complex surgery and post-operative management, limiting its promotion in clinical applications. 3D printing technology provides more diverse choices for patients to select prosthetic limbs [3]. The advancement of 3D printing technology can create models more rapidly, and lower the cost of developing prostheses by using more economical materials and low-cost printers, alleviating the difference in access to prosthetic care around the world [4].

The design and manufacture of bionic prostheses can be customized according to different needs and purposes, such as manufacturing arms, legs, hands, and feet, to help people with disabilities regain their ability to live independently. At the same time, the development of bionic prosthetics can promote the development and cross-application of fields such as biology, medicine, and robotics.

3. Osseointegration technique

3.1. Technical content

Osseointegration aims to firmly connect prosthetics with human bones. This technique involves implanting a small titanium alloy screw into the residual limb bone, and then directly attaching the external prosthesis to the titanium screw through subcutaneous tissue, achieving a strong bond between the bone and the prosthesis.

The primary benefit of using osseointegrated prosthetics is that they can provide more natural and stable mobility while reducing the wear and tear at the interface between the residual limb and the prosthesis. Compared to traditional prosthetics, patients using osseointegrated prosthetics can move and engage in activities more freely without the need for frequent adjustments or replacements.

Titanium alloy materials are mainly used in osseointegration [5]. Titanium alloy has high biocompatibility and can be used in the human body for a long time without rejection. However, surgery is not always successful, mainly due to aseptic loosening and infection of the implant [6], and osseointegration technology is not suitable for patients with osteoporosis, osteomyelitis, and other bone problems. Nevertheless, osseointegration technology is still in its relatively early stages and has vast potential for development with more application scenarios and technical solutions to be explored in the future.

3.2. Example

An Australian team conducted a rehabilitation and outcome-tracking protocol called OGAAP-1 on a total of 50 unilateral transfemoral amputees. The team offered two prosthetic options for bone-anchored reconstruction: Integrated Leg Prosthesis (ILP) and Osseointegrated Prosthesis (OPL) [7].

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Table 1. Pre-and post-operative amputation mobility predictor [7].

Pre·and post-operative K-levels	Patients (n)
Improved	30
K0 to K2	2
K0 to K3	12
K0 to K4	1
K1 to K3	1
K2 to K3	11
K3 to K4	3
Unchanged	20
K2	2
K3	13
K4	5
Reduced	0

K0: The patient is incapable of securely ambulating or transferring with or without help, and a prosthesis does not improve their mobility or quality of life. K1: Patient is capable of using a prosthesis for transfers or ambulation on flat surfaces with a fixed cadence, such as a conventional restricted or unlimited household ambulator; A typical community ambulator, a K2-patient has the capacity or potential for ambulation and the ability to navigate low-level environmental barriers like curbs, stairs, or uneven terrain. K3: The patient has the capacity or potential for variable cadence ambulation, is a typical community ambulator capable of navigating most environmental barriers, and may engage in rehabilitative or exercise activities requiring the use of a prosthesis beyond simple locomotion; K4: Patient exhibits high impact, stress, or energy levels characteristic of the prosthetic demands of the youngster, active adult, or athlete, and has the capacity or potential for prosthetic ambulation that exceeds basic ambulation skills.

Of the 50 patients, 27 experienced complications after surgery, with 10 undergoing soft tissue revision surgery, 21 developing infections, and 4 experiencing falls (3 of whom had severe osteoporosis).

The chart shows that 60% of the patients had improved mobility, with most reaching K3 levels. According to the team's protocol, patients could achieve walking without assistive devices after approximately 4-5 months post-surgery. Patients reported significantly improved satisfaction, quality of life, and physical abilities. However, bone-anchored reconstruction is limited to patients with sufficient bone density and free of infection, and the technique still faces challenges such as sterile loosening and infection.

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4. Electromyographic (EMG) interface technology

4.1. Technical content

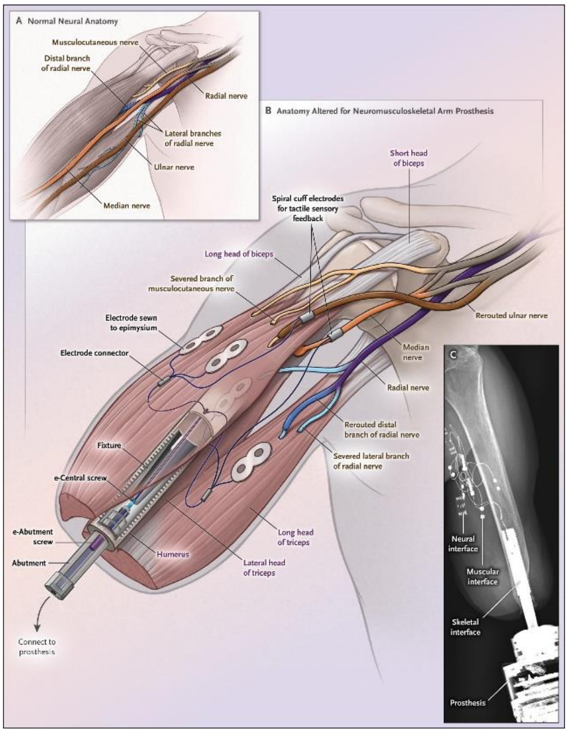

Figure 1. Neuromusculoskeletal arm prosthesis with targeted muscle reinnervation [10].

Electromyographic signals (EMGs) are the most widely used control signals in bionic limbs and have a history of 50 years [8]. Muscle-nerve interface (MNI) technology is a technique that detects muscle signals and transmits them to external devices. MNIs typically use electrode patches or arrays, while the motor and somatosensory cortices can interact with the residual limb. When generating a movement tendency, these electrodes can detect and capture contraction signals on the residual muscles of the patient, and convert them into signals that control external devices, thus achieving prosthesis control [9]. Amputation can affect the function and quality of residual limb muscle fibers, leading to atrophy, spasm, and/or pain. These problems can affect the quality of residual muscle activity and EMG signal in prosthesis control. Therefore, residual muscles must be stabilized with appropriate tension on muscles or bones [10]. Therefore, the type of surgical technique used in amputation is crucial for the preservation of muscle tension and length, recruitment of motor units, and proprioception.

4.2. Application example: self-sustaining neuro-musculo-skeletal prosthetic arm

A team led by Dr. Max Ortiz-Catalan performed a neuro-muscle-skeletal surgery on four patients in 2020, in which electrodes were sutured onto the fascia of the biceps brachia’s two heads, as well as the long head and lateral head of the triceps brachii (Figure 1). These electrodes detect contraction signals of the residual limb to activate the prosthesis motor. Additionally, electrodes were placed near the ulnar and median nerves to deliver electrical stimulation into the nerve fibers to transmit tactile feedback signals on the prosthetic thumb [11].

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5. Prosthetic sensing technology

5.1. Technical content

Prosthetic sensory feedback technology refers to the integration of sensors and feedback mechanisms into prostheses, enabling users to perceive and control the movement of their prostheses, thereby enhancing their function and adaptability. Sensory feedback is critical in daily life, as it eliminates the need for continuous visual monitoring, which is slower and more error-prone without feedback [12].

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5.2. Application example

A laboratory at MIT has developed more precise and stable prosthetic control through antagonistic muscle interface technology (AMI). Antagonistic muscles are a pair of muscles that work together around a joint; when one muscle contracts, the other relaxes [14]. AMIs connect the antagonistic muscle pairs around the residual limb, collect information on the length and force of the residual limb's stretching muscles during prosthetic use, and transmit this information to sensors. The sensors then send electrical signals to the central nervous system, allowing patients to perceive the prosthetic's force and impedance information and achieve a natural proprioceptive sensation [15].

6. Conclusion

This study analyzes the breakthroughs and experimental cases of bionic limb technology in various fields in recent years and argues that in the future, bionic limbs will make prosthetics more similar to natural limbs, both in terms of function and appearance. The clinical applications of osseointegration, cognitive biological screens, implanted sensors, advanced control algorithms, and myoelectric interface technologies will become more widespread. Osseointegration technology provides prosthetics with more degrees of freedom and has already been applied clinically. Compared to brain-machine interfaces (which control prosthetics through conscious thought), controlling prosthetics through myoelectric interfaces is easier to achieve. At the same time, interdisciplinary collaboration and communication need to be strengthened to promote the innovation and development of bionic limb technology to better meet humanity's growing health and lifestyle needs.

References

[1] Roshan James, Cato T. Laurencin. Regenerative engineering and bionic limbs. Rare Metals volume 34, 143–155(2015).

[2] Bensmaia, S.J., Tyler, D.J. & Micera, S. Restoration of sensory information via bionic hands. Nat Biomed Eng (2020).

[3] Román-Casares, A.M., García-Gómez, O. & Guerado, E. Prosthetic Limb Design and Function: Latest Innovations and Functional Results. Curr Trauma Rep 4, 256–262 (2018).

[4] Kyle Silva, Stephanie Rand, David Cancel, Yuxi Chen, Rani Kathirithamby, Michelle Stern, Three-Dimensional (3-D) Printing: A Cost-Effective Solution for Improving Global Accessibility to Prostheses, PM&R, Volume 7, Issue 12, Pages 1312-1314(2015).

[5] Tharani Kumar S, Prasanna Devi S, Krithika C, et al. Review of metallic biomaterials in dental applications. Journal of Pharmacy and Bioallied Sciences, 2020, 12(5): 14-19.

[6] Lu Xiaoxuan, et al. Research Advancements of Coatings of Titanium Implants in Promoting Osseointegration and Preventing Infection. Chinese Journal of Biomedical Engineering. 2021,10: 621

[7] Al Muderis M, Tetsworth K, Khemka A, Wilmot S, Bosley B, Lord SJ, Glatt V. The Osseointegration Group of Australia Accelerated Protocol (OGAAP-1) for two-stage osseointegrated reconstruction of amputated limbs. Bone Joint J. 2016 Jul:962-960

DOI: 10.54254/2753-8818/21/20230857

[8] Smith D 2004 Atlas of Amputations and Limb Deficiencies: Surgical, Prosthetic, and Rehabilitation Principles 3rd edn (Rosemont, IL: American Academy of Orthopaedic Surgeons) General principles of amputation surgery 21–30
[9] Scheme, Erik, Englehart, Kevin. Electromyogram pattern recognition for control of powered upper-limb prostheses: State of the art and challenges for clinical use. Journal of Rehabilitation Research & Development. 2011, Vol. 48 Issue 6, p643-659.
[10] M. Atzori and H. Müller, Control capabilities of myoelectric robotic prostheses by hand amputees: A scientific research and market overview, Front. Syst. Neurosci., vol. 9, Nov. 2015.
[11] Longo MR. Distortion of mental body representations. Trends Cogn Sci. 2022;26(3):241–54.
[12] Max Ortiz-Catalan, Ph.D., Enzo Mastinu, Ph.D., Paolo Sassu, M.D., Oskar Aszmann, M.D., et al. Self-Contained Neuromusculoskeletal Arm Prostheses. N Engl J Med 2020; 382:1732-1738
[13] Hannes P. Saal, Sliman J. Bensmaia, Biomimetic approaches to bionic touch through a peripheral nerve interface, Neuropsychologia, 2015, Pages 344-353,
[14] Shriya S. Srinivasan, et al. Towards functional restoration for persons with limb amputation: A dual-stage implementation of regenerative agonist-antagonist myoneural interfaces. Scientific Reports 2019
[15] Farina, D., Vujaklija, I., Brånemark, R. et al. Toward higher-performance bionic limbs for wider clinical use. Nat Biomed Eng (2021).