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Design and Function of Lower-Limb Prosthetics Based on Biomechanics and Bionic Simulation Using Deep Learning

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Abstract: By mimicking the biomechanics of a missing biological leg, robotic prosthetic legs hold the potential to significantly enhance mobility and quality of life for millions of lower-limb amputees. Unfortunately, compared to traditional passive prosthetics, existing powered prosthetics are heavier, bulkier, and have shorter battery life, which severely limits their clinical feasibility and hinders their practical use in the daily lives of amputees. This paper reviews and explores optimization strategies for the design of bionic robotic prosthetic legs, focusing on challenges related to the stability of biomechanical bionic prosthetics in complex terrain. It discusses how advancements in materials, structural design, and sensor technology can improve stability and adaptability. In the future, biomechanical bionic prosthetics will become more intelligent and personalized. They will possess features like automatic adjustment, 3D - printed customization, and the capacity to modify control parameters and movement patterns in accordance with individual requirements. The research also highlights the potential of neural interface technology to bring new opportunities for biomechanical bionic prosthetics, enabling natural control, efficient signal transmission, and the integration of virtual technologies to assist in rehabilitation.

Keywords: Sensory feedback, biomechanics, conventional prosthetics, powered prosthetics, regenerative mechanical energy

1. Introduction

In recent years, significant progress has been made in biomechanical bionic prosthetics for the lower limbs. In terms of design, integrating ergonomics and biomechanics principles has allowed for a highly accurate reproduction of natural limb movement patterns. The use of novel materials has made prosthetics lighter and more durable, better simulating the human musculoskeletal system. The combination of sensors and intelligent algorithms enables the prosthesis to adjust in real time based on terrain and walking intent. This not only allows for adaptation to complex environments, such as stair climbing and walking on slopes, but also effectively disperses impact forces, reducing pressure and potential damage to the residual limb. The precise motion feedback mechanisms provide users with more intuitive control, significantly enhancing walking stability, comfort, and flexibility. This brings new hope to people with disabilities, propelling the field of rehabilitation engineering to new heights and laying a solid foundation for the future development of smart prosthetics. Although materials like carbon fiber composites and titanium alloys offer many advantages, there is still insufficient research on how their performance may change over long-term use. Whether the strength and biocompatibility of these materials will change over time under different environmental conditions is still uncertain. In addition, it is not clear how effective maintenance and inspection procedures can ensure the safety and reliability of prosthetic limbs, especially in sensor technology and control algorithm. This study reviews strategies to optimize stability in complex terrains and improve control algorithms, providing support for enhancing the quality of life and mobility of individuals with disabilities, and increasing their opportunities and confidence in participating in social activities[1].

2. Strategies for Optimizing the Performance of Biomechanical Bionic Lower-Limb Prosthetics

2.1. Innovative Approaches to Enhancing Stability on Complex Terrain

In complex terrains, such as muddy or slippery surfaces, the stability of biomechanical bionic lower-limb prosthetics faces significant challenges. To enhance the stability and adaptability of prosthetics within such environments, innovations can be carried out in multiple aspects. Firstly, in the realm of materials science, the exploration of developing new materials, which possess high friction coefficients and specialized textures for the sole of the prosthesis, can be conducted. For example, some nanomaterials have superhydrophobic properties that can effectively prevent slips on wet surfaces. At the same time, advanced manufacturing processes such as 3D printing can be used to customize the prosthetic sole according to different terrains and user needs [2].

In the research progress of prosthetic design, enhancing the performance of the prosthesis is a key objective, particularly in meeting military needs. From a structural design perspective, drawing inspiration from the biomechanics of the human lower limb is important for optimizing prosthetic joint designs. The goal is to make the prosthesis fit more naturally with the body’s movement. A useful approach in this process is the use of multi-axis joints and elastic components, which can simulate the movement and cushioning functions of human joints. This design aligns with the literature's pursuit of improving the naturalness and functionality of prosthetics. With this design, prosthetics can better adapt to complex terrains, significantly improving stability in such environments and providing strong support for amputee soldiers in various military action scenarios.

Moreover, intelligent materials, such as shape-memory alloys, can be incorporated into modern prosthetic design. As has been explored in the literature, the utilization of these materials allows the prosthesis to automatically adjust its shape and stiffness in response to environmental changes. This not only enhances the prosthetic's adaptability but also moves toward providing users with a more natural and intuitive control experience, aiding in the restoration of sensory feedback and compensating for the current lack of natural body-feel feedback in lower-limb prosthetics. This integration of traditional biomechanical structures with new intelligent materials complements advanced prosthetic design concepts, driving prosthetic technology towards greater efficiency and intelligence [3].

The application of sensor technologies is also crucial for enhancing stability. By installing various sensors such as pressure sensors, accelerometers, and gyroscopes on the prosthesis, real-time monitoring of the prosthesis' contact with the ground, movement state, and force distribution can be achieved. Using advanced signal processing algorithms and machine learning techniques to analyze and process sensor data allows for precise control of the prosthesis movement. For example, if the prosthesis detects a slipping trend on muddy ground, it can automatically adjust the joint stiffness and the friction of the sole to improve stability [4].

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2.2. Optimizing Control Algorithms and Sensor Fusion Strategies

To attain more accurate motion - intent recognition and smoother gait transitions, it is crucial to improve control algorithms and sensor fusion technologies. Regarding control algorithms, methods like Model Predictive Control (MPC) can be utilized. MPC uses feedback from sensors and pre-established prosthetic movement models to predict future states and optimize control commands, leading to smoother and more natural movement of the prosthesis.

Sensor fusion technologies can integrate data from different types of sensors to enhance the accuracy of motion intent recognition. For example, by fusing data from pressure sensors, electromyography (EMG) sensors, and inertial measurement units (IMUs), a more comprehensive understanding of the user’s movement intent and physical condition can be achieved. Deep learning algorithms can then analyze and process the fused sensor data to enable automatic recognition and switching of different motion modes.

Additionally, neural interface technologies can be introduced to directly read the user's neural signals, allowing for a more natural and direct control method. For instance, through implanted electrodes or non-invasive brain-machine interface (BMI) technologies, the user's brain signals can be captured and translated into control commands for the prosthesis. This approach can significantly improve the accuracy and response speed of motion intent recognition [5].

3. Future Development Directions for Biomechanical Bionic Prosthetics

3.1. Trends Toward Smart and Personalized Development

The future of biomechanical bionic prosthetics will be increasingly intelligent and personalized. In terms of intelligence, prosthetics will be equipped with advanced sensors and processors, which are capable of monitoring the user's motion state and environmental information in real - time and automatically adjusting parameters to adapt to different conditions. For example, when the user walks on uneven surfaces, the prosthesis can automatically adjust its height and stiffness to maintain balance. At the same time, prosthetics can be connected to devices such as smartphones for remote monitoring and adjustments, facilitating management by users and doctors [6].

Personalized customization will be an important direction for future prosthetic development. Through 3D scanning and printing technologies, prosthetics can be tailored to fit the user's body dimensions and shape, improving both comfort and aesthetics. Additionally, the prosthetic's control parameters and movement modes can be adjusted according to the user's movement needs and preferences, enabling a more personalized motion function [7].

3.2. Prospects for Neural Interface Technology Integration

The development of neural interface technology brings new opportunities for biomechanical bionic prosthetics. By directly connecting the prosthetic to the user's nervous system, more natural and direct control can be achieved. Currently, neural interface technology mainly includes invasive and non-invasive types. Invasive neural interfaces require the implantation of electrodes into the user's nervous system, which can achieve high-precision signal transmission but comes with surgical and infection risks. Non-invasive neural interfaces use external sensors to read neural signals, offering lower signal precision but being safer and more convenient [8].

In the future, as neural interface technology continues to advance, more efficient and reliable signal transmission may be achieved, providing a more natural and intuitive control method for prosthetics. Furthermore, neural interface technology can be integrated with virtual reality (VR) and augmented reality (AR) technologies to offer users richer sensory experiences and rehabilitation training methods.

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For instance, VR technology can simulate different movement scenarios to help users with rehabilitation training and adapting to prosthetic use [9, 10].

4. Solutions to Challenges Facing Biomechanical Bionic Prosthetics

4.1. Strategies for Addressing Cost and Maintenance Issues

One of the main challenges currently facing biomechanical bionic prosthetics is their high cost and maintenance difficulties. There are several strategies for solving these problems. First, we should integrate resources and cut down production costs by strengthening cooperation among industry, academia, and research institutions. Optimizing the design, adopting mass - production techniques, and reducing material costs can lower the price of artificial limbs. Secondly, it is of great importance to enhance the reliability and maintainability of products. A modular design and standardized interfaces can make maintenance and replacement more convenient. In addition, strengthening after - sales service and technical support will ensure timely maintenance and care for users. Governments and society can also help by providing subsidies and funding to assist people with disabilities in purchasing and using prosthetics. Furthermore, rental and sharing services can be introduced to reduce the financial burden on users. By establishing prosthetic rental platforms, users can select appropriate prosthetics to rent based on their needs, increasing the utilization rate of prosthetics.

4.2. Importance of Rehabilitation Training and Support Services

Rehabilitation training and support services are vital for users of biomechanical bionic prosthetics. Effective rehabilitation training can help users better adapt to the prosthesis, improving its effectiveness and the user's quality of life. Therefore, it is essential to establish a comprehensive rehabilitation training system, offering personalized rehabilitation plans and professional guidance. Rehabilitation training may include physical therapy, exercise training, and psychological counseling. Physical therapy can help users regain muscle strength and joint mobility, exercise training can improve balance and coordination, while psychological counseling can help users overcome mental barriers and boost their confidence [11].

In addition, support services such as psychological counseling and vocational training should be provided to help users integrate into society. Furthermore, public awareness and education about prosthetic technologies should be increased to reduce discrimination and prejudice against people with disabilities, creating a more inclusive social environment.

5. Conclusion

The study of lower-limb function and design in biomechanical bionic prosthetics holds significant practical importance and offers vast development potential. With the continuous advancement of technology, the performance of prosthetic devices in complex movement scenarios will continue to improve.

This paper reviews strategies for enhancing lower-limb functionality, focusing on stability and adaptability in complex terrains, optimizing control algorithms and sensor fusion technologies, and developing efficient energy recovery and storage systems. These advancements are expected to provide smarter, more personalized, and high-performance prosthetic solutions for individuals with disabilities. For example, in terms of stability, the use of new materials, optimized structural designs, and sensor technologies can significantly improve prosthetic performance on complex terrains like muddy or slippery surfaces. The application of model predictive control (MPC), deep learning algorithm and neural interface technology will realize more accurate motion intention recognition and smoother gait transition in the fusion of control algorithm and sensor.

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However, the development of biomechanical bionic prosthetics also faces challenges such as high costs, maintenance difficulties, and insufficient rehabilitation training and support services. To overcome these issues, collaboration between industry, academia, and research institutions is needed to lower production costs and improve reliability and maintainability. A comprehensive rehabilitation training system should be established, offering personalized plans and professional guidance. Public awareness and understanding of prosthetic technologies must also be increased to eliminate discrimination and create a more supportive society for people with disabilities.

In conclusion, the research into lower-limb function and design in biomechanical bionic prosthetics is a challenging yet promising field. With continuous effort and innovation, future prosthetic technologies will bring more hope and convenience to individuals with disabilities, contributing significantly to social progress and development. Although this paper has some limitations, such as a limited number of references, future research could explore biomechanical bionic prosthetics in more detail by incorporating additional studies.

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