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On the Design and Optimization of Prosthetic Limbs Based on Intelligent Control

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Abstract:
With the continuous development in intelligent control technology, its application in the design of medical devices is becoming increasingly more widespread. In recent years, intelligent control technology has been widely used in prosthetic hand design and optimization. This review attempts to summarize the current research on prosthetic limbs with intelligent control. This review will introduce the design principle behind prosthetic limbs with intelligent control. It will then introduce different control methods, including one method using biological signals and one method based on machine learning algorithms. In the end, the review will discuss how optimization strategies and clinical application of prosthetic limbs with intelligent control are integrated. Through the analysis of related literature, this review intends to provide theoretical basis and technical guidance for the development of more feasible and user-friendly prosthetic limbs with intelligent control in the future. It also discusses the current challenges and future research directions in this field.

Keywords: Intelligent control; Pprosthetic limbs; Clinical application.

1. Introduction

As more people pursue higher quality of life, the use of prosthetic devices on amputated patients is gradually becoming more popular. Prosthetic devices have become an important means of rehabilitation for amputees. Prosthetic devices not only help amputees to regain the ability to carry out day-to-day activities, but also help amputees to integrate into society again and improve their psychological state. Traditional prosthetic devices have certain limitations in terms of usability. For example, the control method is relatively crude, and it cannot meet the needs of amputees. The intelligent control technology, however, can provide more feasible solutions for the design of prosthetic devices. It enhances the mechanical performance of the device, and it can also improve the quality of life of amputees [1].

In recent years, designers have added new technologies to prosthetics. Electroencephalogram (EEG) and myoelectric control now appear in both research plus commercial devices. A team paired EEG with func-

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tional near infrared spectroscopy (fNIRS) and tested the pair on lower limb prostheses. The data showed that the hybrid signal set let the knee but also ankle joints switch modes without manual input [2]. Myoelectric control serves a different group. Surface electrodes on residual muscles pick up small voltages and translate them into hand or elbow commands. The same signals adjust grip force as well as wrist rotation - the hand closes around a cup with the same speed and force as the opposite side. Users report less effort besides fewer adjustments during the day [3].

These technologies not only make the mechanical performance of prosthetic devices better, but also greatly improve the quality of life of users by improving their psychological well-being. As a result, the recovery of the patients' agency is achieved.

Therefore, it is of great significance to introduce intelligent control technology into the design of prosthetic devices. As can be seen from the above analysis, the design of prosthetic devices should follow the user-centered design principle. This design principle emphasizes that the design of products should take the user as the main body, understand the needs and preferences of users, and design personalized products according to users' needs. Users' satisfaction with products would be improved, and the rehabilitation effect would also be improved [4]. In this paper, we will explore the current situation of intelligent control of prosthetic devices. Discuss the technology used in the design of prosthetic devices, and analyze the quality of life of users and the future research direction.

2. Theoretical Research

2.1 Overview of Intelligent Control Technology

Intelligent control technology is a new level of control technology applied in the process of automation and system management. Artificial intelligence (AI) and machine learning (ML) are used in the decision-making process of control. Intelligent control technology developed from the control technology which needed human assistance and pre-defined algorithms. With the development of modern applications such as industry, health care, etc., intelligent control technology develops rapidly. The control system becomes more adaptive and can learn from the past data and experience without human assistance. The application of AI in control systems improves the efficiency, accuracy of control, and adapts to new situations. Therefore, intelligent control technology plays an important role in modern control systems. The application of intelligent control technology makes the smart manufacturing, autonomous vehicles, intelligent health care systems, etc., develop rapidly.

2.1.1 Definition and Development of Intelligent Control Definition

Intelligent control is a type of control system that uses AI technology to improve the performance of control system. These control systems are designed to learn from the past experiences, adapt to the new situation, and make decisions under the circumstances of lack of complete information or uncertainty. The development of intelligent control systems can be divided into three generations. In the 1980s, fuzzy logic and neural networks were introduced into control systems. These systems can handle uncertainty and non-linearity of the control process. With the development of technology, more powerful algorithms have been used in intelligent control systems. Now these systems are not only used in process control, but also used in other fields such as robotics and autonomous vehicles for process optimization, predictive maintenance, fault diagnosis, etc. The research of intelligent control technology continues to develop, and the future of intelligent control systems is more autonomous and efficient.

2.1.2 Current Application of Intelligent Control in Medical Devices

Intelligent control technology is widely used in medical devices. It can be used to monitor patients and support health care processes. Intelligent medical devices are using AI algorithms to monitor the patient's health status in real-time, analyze the huge amount of data, and assist the health care professionals in making decisions. Smart prosthetic limbs use intelligent control to provide a more natural experience to the amputees. The device can recognize the user's movement and intention to provide a more intuitive control [1]. Wearable health monitors use intelligent algorithms to monitor the patient's health status and warn the users and health care professionals in the early stage of recovery.

2.2 Prosthetic Research Status and Design Principle of Limbs

2.2.1 The State of Prosthetic Research in China and Abroad in Last 10 Years

Prosthetic research has made rapid progress in recent 10 years due to rapid development of technology. In recent years, research on Prosthetics in China and abroad is more and more focused on the development of Prosthetics which are more functional, more comfortable and more popular. With the help of mechatronics, intelligent artificial limbs with complex motion similar to human limbs have been developed gradually. For example, the Smart Arm platform is a kind of customizable robotic arm, which enables the user to complete the daily work with stronger ability and more flexibility [4]. However, the control scheme and the user's adaptation are still challenges for the researches. The commercial products can't meet the requirements of users with different degrees of disability. The researchers continue to focus on the further study of control algorithm and the application of sensor feedback to improve the user experience and the function of products [5].

3D printing and smart materials are changing the design and fabrication of prosthetics totally. It is possible to produce durable, light, and bio-compatible devices, which are tailored to the needs of each patient.

2.2.2 Mechanical Structure Design of Prosthetics: Kinematic Analysis of Arm Structures and Mode Selection of Drive

Mechanical design of prosthesis is very important for realizing the expected performance and satisfaction of user. Kinematic analysis plays a key role in understanding the range of motion of prosthesis arms, which is used to design the structure of prosthesis with similar range of motion with human arms. By using the modeling method, the motion dynamic of different joint forms can be simulated and then the mode of drive is selected. The choice of motor type is very important to the performance of prosthesis, such as the response and energy consumption. The recent researches have chosen multi-articulated joints, which are more flexible and have greater range of motion, to achieve the motion mode of human arms more closely [5]. The sensor is placed in the mechanical structure to realize the feedback control and make the hands more adaptive to the user's control [4]. In the future, we will continue to improve the mechanical design of prosthesis to achieve more comfortable use, lighter weight and better performance.

2.2.3 Sensor Control Systems: Selection of Sensor, Signal Acquisition and Processing, Control Algorithm

The development of control sensor is very important in the development of prosthesis technology, because the control sensor can be used to provide feedback information on the prosthesis. Choosing the right sensor will be very important in the design of the control system. The sensor that is often used in the design of a control system is an electromyography (EMG) sensor and force sensor that measures forces interaction with the movement [6]. The Signal acquisition and processing technique must be developed well, so that the information that can be obtained from the result of the measurement by the Sensor is meaningful and useful. Maybe we need to use the signal filtering and other algorithms to improve the signal to noise ratio, and these techniques are very important in the process of controlling leg. Besides that, we must design the proper control algorithm that can be used to interpret the signal and use it to control the prosthesis. In recent years, there has been some success in making the prosthesis more adaptive and intelligent using machine learning and artificial intelligence technology; the prosthetic limb can learn the behavior of the wearer and adapt its function accordingly. In the future, we will continue to focus on improving these systems.

2.2.4 Comparative Analysis of Real Cases

In this part, the comparative analysis of real cases will be described. The comparative analysis of real cases can help the researcher to understand the performance and effectiveness of the design of the prosthetic devices and technologies. By comparing the experiences of the users of different cases, we can find out the advantages and disadvantages of the current prosthetic devices. For example, it has been reported that the multi-grip myoelectric hand prosthesis users have better experiences and more functionality compared with the fixed-function prosthetic hand [5]. In addition, the comparative analysis of real cases of advanced prosthetic technology, such as 3D printing and smart material, has also proved that the advanced prosthesis has more advantages in terms of comfort, fit, and usability [4]. The comparative analysis of real cases not only can provide feedback information for the next design, but also can help the researcher to focus on the user-centered design. In the future, the researchers can design more effective and suitable prosthesis according to the requirement and preference of the user.

2.2.5 Mechanical Design and Material Selection

The frame and the material chosen for a prosthetic limb decide how well it works, how long it lasts and how it feels on the skin. Advancement in material science supplies light, tough plus body-safe matter that engineers now build into limbs. Carbon-fiber cloth bonded with resin and high-grade plastics drop mass yet keep the frame strong [7]. The chosen material also sets how much the limb bends and how it dampens impacts, two factors that let the gait copy a natural stride. Teams now test fresh matter that owns the best mix of characteristics but they also form it through methods such as three-dimensional printing, a process that stacks layers into shapes impossible to mill [4]. The next step will be matter that senses load, heat or moisture and then alters its own stiffness or shape, a shift that will give future limbs new abilities.

2.2.6 Integration of Sensors and Actuators

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The integration of sensors and actuators into prosthetic limbs is another important aspect of modern prosthetic design. This integration enables the development of smart prosthetics that can respond to user intentions and the environment in real time. For example, by integrating EMG sensors and advanced actuators, prosthetic limbs can now perform various complex movements that are similar to those of natural limbs [6]. Feedback control systems can also ensure that the movement of the prosthetic device responds to sensory input, thereby improving the overall performance of the device. Research is ongoing to explore new approaches for integrating sensors and actuators, such as using flexible electronics and soft robotics, which may offer more natural and intuitive interactions between the device and the user [5]. As technology advances, the focus will be on further developing seamless integrations to improve the usability and adaptability of prosthetic devices.

2.3 Research Progress on Intelligent Control Strategies for Prosthetic Limbs

In recent years, there has been a significant development in the field of prosthetics, especially in the area of intelligent control strategies for artificial limbs. These intelligent control strategies have improved the functionality and user experience of prosthetic devices, making them more intuitive and responsive to users. Biological signals and machine learning algorithms play important roles in these intelligent control strategies. In this section, we will discuss the research progress on intelligent control strategies for prosthetic limbs in three aspects: control methods based on biological signals, machine learning-based control algorithms and other strategies.

2.3.1 Control Methods Based on Biological Signals

Control approaches using biological signals such as electromyography (EMG) and electroencephalography (EEG) have attracted increasing interest in the design of intelligent prosthetic limbs. These approaches use the electrical signals produced by muscle contractions or brain activities to control the movements of the prosthetic device. Recently, researchers have explored the possibility of using electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) in combination to decode neural signals for more intelligent control of lower limb prosthetics [1].

Many studies have investigated the recruitment patterns of different muscles in amputees to provide insights for myoelectric control system design. For example, researchers have investigated the muscle activities between the intact limbs and residual limbs in amputees, and found consistent recruitment patterns of muscles during different functional movements [3]. Such information can be used to design better myoelectric control approaches for prosthesis control. In addition, soft robotic actuators have been incorporated into the sockets of prosthetic devices, and experimental results have shown that the device is able to achieve adaptive control based on tactile and temperature feedback, improving the comfort of the device [8].

2.3.2 Control Algorithms Based on Machine Learning Algorithms

Algorithms based on machine learning have also been used for controlling prosthetic limbs. These approaches use the large amounts of data acquired from different sensors to train the models, and the models allow the prosthetic limbs to make real-time adjustments to their movements based on the user's intentions and environmental conditions. Recently, researchers have used neural network models to predict and fit dynamic grip forces based on surface electromyographic (sEMG) signals, showing the potential of machine learning in improving the performance of prosthetic control [9]. A customizable robotic arm platform has also been developed and used as a test bed for different control laws and command signals for upper limb prosthetics. This platform allows researchers to explore different machine learning techniques such as reinforcement learning to optimize the control of the prosthetic devices [4].

The studies discussed above have used different strategies to improve the performance of prosthetic devices, but these strategies focus on biological signals and machine learning. Other strategies have also been reported, including using force sensors embedded in the prosthetic devices to measure the structural loads generated during gait, which provides feedback for controlling the movements of the prosthetic device and improving its stability [10]. The sensors enable the prosthetic device to detect different gait events such as the heel strike and toe off events, and these events help the device achieve more natural and efficient movements.

Furthermore, many studies have focused on using soft robotics and adaptive materials in prosthetic design. For example, new designs using smart polymers in the prosthetic socket have emerged, which fit the shape of the user's residual limb and change accordingly [11]. This solves many problems associated with socket fit, which is a major cause of prosthesis abandonment.

In general, the development of intelligent control strategies for prosthetic limbs has made significant strides, and these advances in design are leading to more efficient and user-friendly prosthetic devices. As these technologies mature, highly adaptive and intuitive prosthetic devices are becoming increasingly attainable.

2.4 Application of Optimization Algorithms in Prosthetic Design

The application of optimization algorithms in prosthetic design has been widely studied. Optimization is an important step in the design process of a prosthetic device. The optimization process usually focuses on the weight, amount of material, and other parameters of the prosthetic limbs. By applying optimization algorithms, the design of the prosthetic device can be improved. The design process can be enhanced with the help of optimization algorithms. The results of different configurations and parameters are simulated and analyzed. This leads to better designs of prosthetic devices. These designs not only make the devices more comfortable for users, but also improve the efficiency of the device.

2.4.1 Design Optimization Objectives and Measures

Design optimization of prosthetic devices is primarily aimed at enhancing functionality, comfort to the user, as well as durability. The most significant metrics that enhance this process are weight-reduction, material-selection and biomechanical performance. To put it basically, we should make the prosthesis as light as we could make it. A heavier device results in fatigue and pain to the user and thus the weight reduction is the important aspect in ensuring comfort to the user. The other crucial element is that of selecting the appropriate material to construct the device, we need to be able to assure durability, high performance on the device whilst making it lightweight. Biomechanical performance meter defines the ability of the device to replicate the motion of a natural limb, and this makes the experience more natural and comfortable. By accomplishing such goals and metrics, the end result, the prosthetic devices, actually benefit the mobility and quality of life of the user [2].

2.4.2 Comparative Study of the Advanced Optimization Algorithms

In this case we compare the performance of various advanced optimization algorithms and their application to the design of prosthetic designs. It has been used with genetic algorithms, particle swarm optimization, simulated annealing and numerous others, each having varying degrees of success. Genetic algorithms search a huge design space using genetic selection, and ultimately arrive at a good solution. Particle swarm optimization is characterized by a fast convergence rate and simple to implement thus it is an appropriate model to be used in real-time to design a prosthetic. Local minima can be overcome by a probabilistic search in simulated annealing. The selection of algorithm normally relies on the problem, the time of computation, the quality of solution and the kind of optimization activity being undertaken.

2.5 Clinical Implementations and usability

2.5.1 Smart Prosthetics Clinical Trials and Effectiveness Assessments

Clinical trials and effectiveness evaluation have supported the development of smart prosthetics as they seek to enhance the quality of life of amputees. Recent work indicates incorporation of technologies like EEG (electroencephalography) and fNIRS (functional near-infrared spectroscopy) into smart lower-limb prostheses and providing the ability to intuitively control the device by decoding neural signals and demonstrates potential to improve user-experience and functionality in the rehabilitation environment [1]. In prosthetics of the upper limb, scientists remain unable to recreate the natural sensorimotor control, a significant obstacle in neuro-engineering [2]. Trials on transtibial amputees have investigated muscle activity patterns which would be useful in developing more effective myoelectric control schemes. The trials have also established that consistent patterns of recruitment could be found between subjects [3].

Also, a device known as the Smart Arm was created, which enabled the testing of different control schemes in real time with the real amputees and it is possible to see that the smart prosthetics can bridge the functionality gap [1]. User feedback shows that user-friendly gadgets that are comfortable to use are very important especially those that are capable of facilitating daily activities. Individual exercise regimens were found to enhance balance and confidence among lower-limb amputees substantially, indicating the need to exercise care when it comes to customized rehabilitation so as to optimize the utility of smart devices. Finally, clinical trials, effectiveness tests, and feedbacks can all play an important role in developing smart prostheses that can indeed improve the functionality and quality of life.

2.5.2 Smart Prosthetic User Experience and Development Future

One of the determinants of the adoption and usage of smart prostheses is user experience. The design and functionality of the future devices will depend on the acceptance of the users and therefore the designers will need to take into consideration the user feedback in designing the device. To illustrate, weight, appearance, and sensory feedback are commonly mentioned by the users of upper-limb prostheses, which indicates that the present smart prostheses are not fully satisfactory according to

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the user expectations [12]. Additive manufacturing and soft robotics are introduced as the solutions to mitigate these fears with more functional and personalized designs at a reduced cost [13]. Artificial intelligence and machine learning as another sophisticated technology are also recommended to be implemented in future smart prostheses to provide interactions with users and modify themselves to their needs and preferences. Virtual reality has already been used in rehabilitation and training of prosthetic users, where it can offer the users an immersive experience and encourage the user to engage more in training [14].

Overall, more intelligent and personalized devices will be created by creating smart prostheses that react to user reactions and experiences. Further advancements in smart prostheses will be more acceptable to their end-user and perform better functional levels, as they will combine the most recent technologies and rehabilitation techniques.

3. Conclusion

In recent years, intelligent control technology has been widely applied in the design and optimization of prosthetic devices. As discussed in this review, advanced design principles, control strategies, and optimization algorithms provide an effective approach to enhance the functionality and adaptability of prosthetic devices. These intelligent control technologies not only focus on the mechanical and functional deficiencies of prosthetics but also provide more user-centered solutions.

From the experts' point of view, there are many different findings and perspectives existing in this field, and expert understanding of intelligent control system cannot be simplified as a simple sum of its constituent findings. It is also important to balance the technical findings in the process of control algorithm derivation and practical information obtained from clinical application. It is important for researchers to collaborate and work in the interdisciplinary field of engineers, clinicians, and users to develop more advanced prosthetic devices that are not only technologically advanced but also have real-world usability and user preferences.

Furthermore, users' feedback should be taken into account in the design process. In the future, more personalized design approaches should be developed to meet the anatomical, functional, and lifestyle requirements of users. This trend of customization is likely to increase user satisfaction and improve functional outcomes. By collecting data and analyzing it with machine learning methods, designers can better understand the differences in user experience and preferences, which will help improve the adaptability of future prosthetic devices in different environments.

In conclusion, while the current advancements in intelligent control technologies for prosthetics are promising, the future of this field will hinge on our ability to synthesize technological innovation with user-centered design principles. The path forward involves not only pushing the boundaries of what is technically possible but also ensuring that these innovations resonate with the lived experiences of prosthetic users. Continued interdisciplinary collaboration, along with a strong focus on personalized solutions, will be critical in achieving the ultimate goal of enhancing mobility, independence, and quality of life for individuals relying on prosthetic devices.

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