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Research Progress on Prosthetic Feedback

Hongyi Xin[1,a,*]

[1]*School of International Education, Beijing University of Chemical Technology, Beijing, 102200, China*

a. 2022090104@buct.edu.cn

**corresponding author*

Abstract: At present, prosthetics are becoming more functional, but most prosthetics have no feedback function, which does not allow users to adjust some movements independently. More research is needed to develop prosthetic feedback. Based on the literature, this paper reviews the relevant research on prosthetic feedback, and probes into the meaning, characteristics, advantages and disadvantages, problems and future development of each method from electrohaptic feedback, pressure feedback and vibration feedback. Based on the comparison of these three feedback methods, it is found that electrohaptic feedback is excellent in fine control and multi-channel feedback; Pressure feedback has advantages in simulating real touch and improving operational confidence; Vibration feedback, with its low cost and simple operation, has the potential for widespread application. Each technology possesses its distinct application scenarios and advantages; however, there are also challenges that need to be surmounted. As the technology continues to advance, it is expected that these haptic feedback technologies will provide users with a richer and more natural interactive experience.

Keywords: Bionic prosthetics, Electrotactile feedback, Pressure feedback, Vibration feedback, Sensory feedback

1. Introduction

After years of development, the function of prosthetics has evolved from being purely aesthetic to replacing most of the functions of the original limb. However, most prosthetics still do not move naturally. One reason for this is that prosthetics lack feedback features that enable users to independently adjust certain movements. Many studies have focused on sensory feedback of prosthetic limbs, believing that sensory feedback is an important direction for prosthetic limb control and improvement of prosthetic limb use [1,2]. Yuan et al. used vibration motors to transmit feedback to improve amputees' control of prosthetics [3,4]. Zhu proposed the application of electrotactile feedback system in his research. Based on this, some researchers studied sensory afferent fibers to improve the balance and walking of those who improved the calf cutoff through tactile feedback [5,6]. Some researchers use the stimulation electrode array to realize the haptic feedback of the prosthetic hand and complete the closed-loop control of the prosthetic [7-10]. The purpose of this paper is to summarize the previous research progress on prosthesis feedback, help people in need to quickly understand the way of prosthesis feedback, and explore more possibilities of prosthesis feedback.

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2. Overview of electrotactile feedback

2.1. Electrotactile feedback

Electrohaptic feedback technology simulates the sense of touch through electrical stimulation to help people with amputations or nerve injuries improve their grip and quality of life. It is non-invasive, simulates a real sense of touch, and enables region-matched feedback. [1,2,7-10]

2.2. Features

The characteristics of the electrohaptic feedback system include multi-channel capability, which enables it to provide haptic feedback at multiple points simultaneously, enhancing the perceptual accuracy and the ability to control the prosthesis naturally. Also, it is real-time. The system can respond to the prosthesis operation and external interaction in real time, offering fast tactile feedback. [2] User-friendly, simple and intuitive design, easy for new users to quickly get started; Customized, can adjust the stimulation intensity and mode according to user needs, to provide personalized experience [9]; Technical advantages, simple operation, light, efficient, high resolution, easy to control by computer; Non-invasive, no surgery, safer, suitable for long-term wear [1]; Highly customized, adjustable stimulation parameters to provide a rich tactile experience; Portability, designed as a wearable device for easy portability [2]; Multi-channel stimulation that provides comprehensive sensory feedback through multiple stimuli; High spatial resolution, provide force, touch, pressure and other rich feedback, improve the perceptual accuracy; Instant feedback, featuring fast perception and feedback, helps users interact naturally. Plasticity is another characteristic, as it can be adjusted according to environmental and task changes, adapting to different scenarios [1].

2.3. The advantages and disadvantages of the feedback and future prospects

The advantages of electrohaptic feedback system include improving interactive experience, simulating real touch, and improving the naturalness and accuracy of grasp and operation, especially in low light or poor sight environment; Improve the usability of prostheses, and enhance the fine motor control and rehabilitation training of prostheses through fine adjustment of stimulation parameters; Non-invasiveness and safety, reducing the risk of invasive haptic feedback and providing safe and reliable options [1,2]; Enhancing interactive experience and reducing visual burden, providing intuitive operational feedback and reducing visual stress in applications that focus visual attention for long periods of time; Suitable for virtual reality and teleoperation, providing intuitive feedback in remote operation scenarios to enhance user experience; Enhance prosthesis control, provide natural and fine operation feedback, improve prosthesis control effect, reduce phantom limb pain, and enhance the sense of identity; A wide range of tactile simulation, simulating a variety of tactile sensations, such as pressure, texture, roughness, etc., to enrich users' sensory experience; Improve the quality of life and independence, restore the tactile function, help the disabled better perceive the environment, improve the quality of life and independence [2].

Electrohaptic feedback technology, while promising, faces some drawbacks: technical limitations, and further research is needed to optimize the stimulation pattern and intensity to provide a more natural tactile simulation; User discomfort, electrohaptic feedback may contain feelings that the user does not like, such as a burning sensation [1,10]; Individual differences, the perception and response to electric current vary from person to person and need to be personalized adjusted; Customized requirements, the system needs to be customized according to the specific situation of the user, increasing the complexity of technical implementation; Cost issues, high quality equipment may cost high, limiting the wide application [8]; Control and programming

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challenges, requiring precise control and programming to produce accurate haptic effects; Multiple sensory effects, electrohaptics may include a variety of sensations, such as tingling, itching, etc., affecting the user experience. In general, electrohaptic feedback technology needs to address challenges such as technical limitations, user discomfort, individual differences, customization needs, cost and control programming to improve the user experience.

Electrohaptic feedback technology is promising in areas such as prosthetics, wearables and virtual reality, but it is still in development and faces technical and operational challenges. To improve the tactile realism of this technology, it is necessary to: precisely control the electrical stimulation, analyze the tactile data through algorithms, and adjust the current parameters to simulate different tactile sensations [7,8] User feedback: The collection of user feedback enables personalized adjustment of the system, improving satisfaction and facilitating technology research and development. Reducing discomfort: By optimizing electrical stimulation parameters and developing new materials, biocompatibility and comfort can be enhanced. Technical standardization: Establishing standards and protocols helps improve the compatibility and interoperability between devices. Commercialization and user acceptance: Collaborating with different fields accelerates commercialization, increases user acceptance, and educates users about the advantages of the technology through education and experience opportunities.

The development of electrohaptic feedback systems relies on improved accuracy and user experience. In the future, personalized solutions can be developed to meet the needs of different users; Interdisciplinary research, combining machine learning and neuroscience to optimize parameter selection and improve stimulation effects; Data analysis, using accurate algorithms to analyze tactile sensor data to improve personalization and accuracy; Multi-sensory combination, combining electrotactile with visual and auditory feedback to provide a comprehensive sensory experience [10]; New stimulation methods, exploring new methods such as transcranial direct current stimulation (tDCS) or transcranial magnetic stimulation (TMS) to provide a more comprehensive sensory experience [2]; Technological advances, with future devices likely to have higher resolutions, better user interfaces and wider applications; Technological innovation to promote the application of electrohaptic feedback technology in medical treatment, rehabilitation, industry and other fields; Technical challenges, current guidance technology research, improve the resolution of electrical stimulation; Individual differences, considering the individual's sensory threshold and sensitivity to the current, personalized adjustment; Cost issues, high quality equipment may be costly and limited to a wide range of applications, but it is expected that with technological progress and cost reduction, the application will be more extensive [8]. In summary, electrohaptic feedback technology is enhancing the user experience and the scope of applications via personalization, interdisciplinary research, and technological innovation.

3. Overview of pressure feedback

3.1. Pressure feedback

Forced-haptic feedback is a technology capable of simulating tactile perception by providing tactile feedback to the user through special devices (such as vibrating motors, pressure sensors, etc.) to enhance the user's perception of the interactive object. In the control system of prosthetic hands, force-haptic feedback can help improve the user's grip accuracy, reduce the reliance on visual feedback, and improve the user experience. [1,2,5]

3.2. Features

Force-haptic feedback systems enable the user to sense the force and texture of the prosthetic's contact with the object by simulating real touch, such as vibration and pressure. The system can monitor the condition of the prosthesis in real time, allowing users to accurately perceive motion and force even without relying on vision, improving the accuracy and efficiency of the operation [2]. This is especially important for operating prosthetics in situations of poor light or visual impairments, reducing the reliance on visual information and helping users rely on haptic feedback to complete tasks.

3.3. The advantages and disadvantages of the feedback and future prospects

The main advantage of forceshaptic feedback technology is to improve perception and control. Through precise tactile signals, users can perceive the subtle changes in the contact between the prosthetic hand and the object, adjust the force, and achieve fine operation; Simulating the real sense of touch, allowing users to feel the texture, shape and temperature of the object, providing a more natural interaction experience; Improve operational satisfaction, enhance user confidence and social engagement, and make daily activities more comfortable; Reduce visual dependence, in the visual impairment or poor light environment, through tactile signals to assist users to operate the prosthetic limb, reduce the visual burden [2]; Adapt to a variety of environments, in dim light or crowded environments, to provide users with the necessary assistance to make activities more comfortable.

Haptic feedback technology confronts several major challenges: Individual differences, the necessity to customize and adjust the intensity and pattern of haptic feedback for each user, which raises the complexity and cost of prosthetic hands; Technical challenges, the requirement to enhance the accuracy, speed and energy consumption of feedback, especially in areas such as surgical robotics, where precise force-tactile feedback is crucial for reducing surgical risk. [1]. The high cost of advanced haptic feedback systems is a barrier to promoting their applications in areas such as consumer electronics and virtual reality, and a balance needs to be found between performance and cost. Overall, haptic feedback technology needs to address individual needs, technical challenges, and cost issues to improve user experience and operational efficiency.

Force-haptic feedback systems face challenges in improving the feedback accuracy of prosthetic hand interaction with objects, requiring optimization of sensors and signal processing. The system also needs to be personalized and adjustable to suit the tactile perception and preferences of different users. Through the EMG decoding technology, the feedback mode can be adjusted to make the operation more in line with the user's expectations. Integrating force-haptic feedback into a prosthetic hand control system is a complex engineering challenge that involves the integration of hardware and software [5]. In short, force-haptic feedback systems need to improve accuracy, personalization, and system integration to better reflect the state of the prosthetic hand's interaction with the object.

Forces-haptic feedback technology is advancing rapidly due to advances in haptic sensors, machine learning, and machine vision, providing a more realistic tactile experience. In the future, user research can be developed to optimize the design through user feedback and behavioral data to make the system more ergonomic and user habits; Cost reduction, technology maturity and scale production reduce costs, enabling more consumers and enterprises to afford and adopt the technology; Policy support, with the government issuing policies and regulations to support technology research and development, commercialization and standardization; Portability and comfort, research into more lightweight, thin and miniaturized devices that are easy to carry and integrate into smart devices [5]; Fast response, improving algorithms and hardware design to improve the device's response speed and sensitivity to accurately respond to user actions [1]; Improve accuracy, improve system resolution and accuracy, develop new sensors, improve signal processing and force feedback actuator performance; Materials and miniaturization technology to

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develop lighter and smaller force feedback devices to provide high quality haptic feedback and integrate into various devices.

4. Overview of vibration feedback

4.1. Vibration feedback

Vibration feedback is a sensory feedback technique that helps users perceive and adjust their behavior through vibration feedback to users. In the application of leg prosthetics, vibration feedback system helps users improve their gait, balance function and walking ability by providing vibration feedback according to the user's motion state and set parameters while the user is wearing the prosthesis. [1,2,5]

4.2. Features

Vibration feedback technology possesses the following characteristics: It is easy to operate, and its settings and adjustments are straightforward, reducing learning costs and being widely used. It has a low cost, enabling more users to afford it and enjoy the convenience brought by the technology. [4]. Small sensory interference, small impact on the forward channel, to ensure the comfort of use.High spatial resolution, providing detailed feedback to help users perceive the environment; Improve gait and balance, help patients adjust gait in rehabilitation training, improve stability, especially for the elderly and people with mobility difficulties. Adjustability, adjustable frequency and intensity to adapt to different user feelings and preferences; Flexibility to adapt to a variety of application scenarios and user groups [3]. And device composition, including gyroscopic sensors and vibrating motors that capture motion states and deliver tactile feedback in real time.

4.3. The advantages and disadvantages of the feedback and future prospects

The benefits of the vibration feedback include ease of use, reduced learning difficulty, rapid adaptation, and reduced need for professional training; Economy and low cost enable more amputees to afford and enjoy convenience [4]; Reduce interference, design consideration to minimize bioelectrical signal interference, improve comfort and functionality; Gait and balance, improving gait symmetry and balance through joint design and adaptive adjustment; Safety, improved materials and design, improved stability and durability, and reduced risk of falls; Acceptance and compliance, improved design, users are more willing to wear for a long time, improve social integration and self-confidence; Practicality and feasibility, technological advances bring functional and comfort improvements, and provide personalized choices [3].

Vibration feedback technology has some limitations, mainly including: low spatial resolution, unable to provide a fine tactile experience, difficulty to simulate complex textures or subtle vibration differences; Low resolution and accuracy, which can make precise operations, such as gesture recognition or keystroke input, difficult; Individual needs, different users have different vibration sensitivity, need to adjust the vibration intensity individually [2]; Adaptability issues, users may need time to adapt to vibration feedback, especially if the vibration is too strong or the frequency is not appropriate [5]; Quality and power consumption, vibrating motors can affect the device's portability and battery life, and are especially important for users who use them for long periods of time. In general, vibration feedback technology presents challenges in providing a fine tactile experience, precise operation, personalized adjustment, user adaptability, and device portability and battery life.

Optimize vibration parameters, adjust vibration frequency and intensity, simulate different tactile information, such as texture and pressure; Combine multiple sensors. Use pressure or capacitance sensors to capture more comprehensive tactile information and convert it into vibration signals [4]; Sensor and motor design, considering sensitivity and response time, using gyroscopic sensors to capture motion states, vibration motors need fast response and precise control; Improve portability and experience, reduce motor mass through lightweight materials and optimized design, and reduce power consumption through improved power management; And special needs considerations, developing customized vibration feedback programs for special users such as hemiplegics to aid rehabilitation training and improve balance and walking function [2,5]. In short, by optimizing vibration parameters, combining multiple sensors, designing highly sensitive motors, improving portability and considering special needs, the accuracy and user experience of haptic simulation systems can be improved.

In order to improve the quality and user experience of vibration feedback systems, the following measures can be taken in the future: Explore complex vibration modes and design vibrations with different intensities, frequencies, pulse waves, and rhythms to simulate more tactile information and enhance the quality of perception. Optimize vibration parameters, conduct studies on human haptic feedback, and determine the appropriate vibration duration and interval to alleviate discomfort [2]. Perform performance testing by using balance instruments, scales, and other tools to detect the vibration feedback system, evaluate its impact, and optimize it. User-friendly design, development of intuitive interfaces and feedback strategies, considering device portability and aesthetics; Collect user data and optimize feedback strategies based on user data to meet a wide range of needs including users with special needs [3]; And with technological advances, future devices will be smaller, consume less energy and have better control systems, which will be applied in fields such as virtual reality, gaming and health monitoring. In summary, the quality and applicability of vibration feedback systems will be improved through optimization of vibration modes, performance detection and user-friendly design, as well as technological advancements [4].

5. Case analysis

Electrohaptic feedback technology offers significant advantages in providing fast and portable tactile simulation, but challenges remain in terms of sensory reconstruction, complexity of device implementation, and precision of sensory mapping. Future research needs to focus on improving the naturalness of stimuli, optimizing mapping strategies, and reducing the complexity and cost of the system. [8] Force-haptic feedback technology plays an important role in prosthetic limb control by transmitting sensory information about the movements and interactions of the prosthetic limb to the user to improve the user's control ability and use experience of the prosthetic limb. Force-haptic feedback can improve the control effect, and force-haptic feedback can improve the control effect of the user on the prosthetic limb, so that the movement is more accurate and natural. This kind of feedback can help users better perceive the state of the prosthetic limb, such as the size of the grip strength, so as to achieve finer operational control. Reduce phantom pain. By providing sensory feedback, force-haptic feedback helps to reduce phantom pain and enhance the user's acceptance of the prosthetic [2]. Reducing cognitive burden, force-haptic feedback can reduce the user's cognitive burden when using the prosthesis because it provides other sensory information besides vision, and the user does not have to over-rely on vision to monitor the movements of the prosthesis. Non-intuitive, although force-haptic feedback has its advantages, the feedback provided may be non-intuitive, as the user needs to be trained to correlate the feedback information with the stimulus parameters, position, etc. Training and adaptation requirements, users often need to go through a lot of training to become familiar with and adapt to haptic feedback, which can make the training process tedious and time-consuming. Technical limitations, due to physiological and technical limitations, only a limited amount of information can be transmitted to the user through the haptic interface, which limits the bandwidth and naturalness of feedback [5]. Invasive vs. non-invasive methods, invasive feedback methods, such as direct nerve stimulation, while providing more natural sensory feedback, are still in the laboratory stage due to surgical risks and limitations in electrode technology. Non-invasive methods, such as transcutaneous electrical nerve stimulation (TENS) and vibratory stimulation, while safer and more flexible, fall short in feeling naturalness. Potential of multimodal feedback, future research may focus on multimodal feedback to provide richer sensory information by combining different feedback modalities (such as mechanical stimulation, electrical stimulation, vibrational stimulation, etc.), thereby improving the control of prosthetics and the user experience [1]. As a kind of prosthetic sensory feedback technology, vibration feedback has the following characteristics and advantages and disadvantages: simple and easy to operate, vibration feedback device is simple, and it is one of the most commonly used sensory feedback methods. Small volume and light weight, the modern vibration feedback device is small in size and light in weight, easy to integrate on the prosthetic limb, and is conducive to improving the portability of the prosthetic limb. Low power consumption, vibration feedback devices usually have low power consumption, which is conducive to extending the battery life of the prosthesis. The cost is relatively low. Compared with other complex feedback systems, the cost of vibration feedback is relatively low, which is conducive to popularization and application. There is no interference to the bioelectrical signal, and the vibration feedback will not interfere with the bioelectrical signal such as the myoelectric signal, which ensures the purity of the signal. The response speed is fast. The vibration feedback can provide timely feedback by rapidly changing the vibration frequency or intensity, which helps to improve the response speed of the prosthetic limb [5]. Resolution limitations, despite the simplicity and accessibility of vibration feedback, humans do not seem to have very high resolution for different levels of vibration, limiting its ability to provide fine sensory feedback. Training and adaptation are required. Subjects usually need a lot of training to become familiar with the prosthesis before they can significantly improve the efficiency of the prosthesis, which increases the burden of learning and adaptation for the user. May not be enough to reduce visual attention, the study found that without a lot of training, simple vibration stimulation feedback does not significantly reduce visual attention, suggesting that vibration feedback may not be enough to completely replace visual feedback. Improve the user experience. After a period of training and use, subjects indicated that the vibration-stimulus feedback significantly improved the user experience of the prosthetic limb [5].

In general, each of the three techniques possesses its own characteristics and is applicable to different scenarios and requirements. Electrohaptic feedback is appropriate for circumstances where fine control and customized experiences are demanded, force-haptic feedback is suitable for situations where the simulation of true strength and motion is necessary, and vibrational feedback is applicable to situations where there is cost sensitivity and simple feedback needs exist. As the technology progresses, these haptic feedback techniques are anticipated to improve further to offer a more natural and precise user experience.

6. Conclusion

Electrohaptics, forces-haptics and vibrational feedback are three main haptic feedback techniques, each with its own advantages and challenges. The benefits of electrohaptic feedback, suitable for prosthetics and wearables, provide a multi-channel, real-time, user-friendly, customised and non-invasive experience for fine control. The challenge is to optimize the stimulus model and address individual differences in adaptability, cost, and user acceptance. The advantages of force-haptic feedback, which provides a naturally rich interactive experience through physical pressure, are suitable for improving grip accuracy and reducing visual dependence, such as prosthetic limb control. The challenges it faces are individual differences, technical challenges and cost issues. The benefits of vibration feedback include low cost, ease of use, suitability for mobile

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devices and rehabilitation training, and significant potential for widespread adoption. However, it encounters challenges related to low spatial resolution and accuracy, which may require user adaptation. Electrohaptic feedback has excellent performance in fine control, forces-haptic feedback has advantages in simulating real touch, and vibration feedback has the potential for widespread application with low cost and simple operation. As technology advances, these haptic feedback technologies are expected to provide richer and more natural interactive experiences.

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