

Enhancing Sensory Feedback in Prosthetics: Current Innovations and Future Directions

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Abstract. With the development of society and culture, people are more and more inclusive and concerned about disabled groups, and the problems and limitations faced by disabled people when wearing artificial limbs are gradually being paid attention to. The absence of sensory feedback in contemporary prosthetics constitutes a fundamental issue, significantly contributing to the reluctance of many individuals with disabilities to utilize these devices. This article summarizes the primary methods to enhance the sensation of prosthetics in the current stage. Current research methods are divided into 3 types: mechanical and electronic sensors, neural interface technology (invasive and non-invasive), and biomimetic materials. These approaches can provide sensory feedback to prosthetic users to some extent. Although temperature sensing in electromechanical sensors is not widely used, this technology can significantly enhance the experience and sense of happiness of prosthetic limb users. Moreover, existing studies have shown that bionic skin can successfully restore some amputees' sense of touch and tingling. However, all current technologies are facing particular challenges and still have excellent future development prospects.

Keywords: Prosthetic sensory feedback, Prosthetic, Temperature sensors, Force feedback, Electrical stimulation

1. Introduction

Losing a limb after amputation can completely change a person's lifestyle. Both their motor and sensory functions will be lost, and as a result, this significantly affects their level of daily activity and their quality of life. Wearing a prosthetic limb can significantly restore their motor ability. However, regaining sensory function remains challenging. It is also a significant factor that causes one in five upper limb amputees to choose not to wear a prosthetic [1]. This article examines three key aspects: the application of human sensory feedback principles to prosthetic limb feedback, the advantages and disadvantages of leading solutions, and the primary challenges currently encountered along with future prospects. The three main approaches currently used to solve this problem are mechanical and electronic sensors, neural interface technology, and biomimetic materials. But now there are also some technical challenges, such as the stability and durability of sensors (non-invasive), and the biocompatibility of neural interfaces (invasive). Not only that, but there are also some moral and ethical issues to solve this problem. Suppose this technology can be

successfully developed in the future. In that case, it will not only help countless prosthetic wearers alleviate both psychological and physical pain, but also enable people with amputated parts to feel the warmth of the world better. Moreover, this technology will also significantly reduce their resistance to wearing prosthetic limbs.

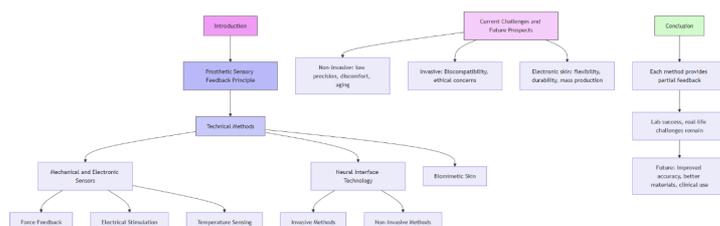


Figure 1: Overview of the structure and key content of this review article. The flowchart summarizes the introduction, major technical methods for achieving sensory feedback in prosthetics, current challenges, future development directions, and the final conclusion.

2. Prosthetic sensory feedback principle

The human body can receive sensory feedback (such as vision, sensation, touch, etc.) because the skin receptors transmit sensory information, such as vision, touch, and pain, to the brain. Subsequent to the acquisition of this information, the brain orchestrates muscular activity to facilitate limb movement via a sequence of "commands," thereby establishing a comprehensive closed-loop system originating from sensory input.. However, for amputees, the missing limbs will block the closed loop, and the skin cannot successfully transmit information to the brain, which makes the closed loop unable to proceed normally, resulting in loss of movement and sensory kinetic energy. Nevertheless, while prosthetic devices can significantly aid amputees in regaining motor function, the restoration of intuitive sensory feedback remains a substantial challenge [2]. Sensory feedback, however, is crucial to restoring physical function in amputees. Although wearing a prosthetic limb does not reconnect the pathway, it can stimulate the wearer of the prosthetic limb by using methods such as electrodes when the patient touches an object, so that they can regain "feeling".

A fully equipped prosthetic device should include haptic sensors and devices for closed-loop prosthetic control. Making a reliable sensing system is the first step to a fully functioning sensory feedback system. A tactile sensing system may comprise various modules of spatially distributed sensing elements, typically shielded by an elastic layer, which is affixed to the surface of the (curved) prosthesis. Consequently, it is imperative that the system exhibits flexibility, alongside exceptional reliability and stability [3].

3. Technical methods

3.1. Mechanical and electronic sensors

Non-invasive methods are mainly divided into mechanical and electronic sensing. Force feedback constitutes a conventional mechanical sensing technique that activates the mechanoreceptors of the skin and the afferent nerve endings, facilitating the transmission of various pressures and the

positional information of body limbs via spatial, frequency, or intensity mapping [4]. One way to make a prosthetic limb feel is through electrical stimulation. Electrical stimulation operates through the implementation of a mobile fingertip pressure sensor positioned externally to the digit, in conjunction with a wearable electronic tactile armband affixed to the upper limb. This configuration facilitates the application of electrical currents that stimulate the peripheral nervous system, thereby translating the sensory input into a tactile feedback mechanism perceived by the body. Temperature sensing is another way to use electronic sensors to make prosthetic limbs feel. This method can help amputees regain their sense of temperature by transmitting the temperature detected by the prosthesis to other intact areas of the patient's skin. However, the sensitivity of different body parts to temperature and the ability to recognize materials are different. To achieve this method, selecting appropriate placement and materials is particularly important [5].

Although this technology is not widely used due to its high difficulty and many technical challenges, it can significantly improve prosthetic users' experience. First, users can feel the temperature of each object through the prosthesis, improving the safety. For example, without temperature feedback, touching a hot object with the prosthesis can burn it. If people touch hot food, people can burn themselves. But with this technology, all of that could be largely avoided. Secondly, this technology not only elevates the temperature of the prosthesis but also infuses life with warmth, enhancing both the overall thickness and breadth of the device. The main thing is that when you hug your loved one, not only can you feel the temperature of your loved one, but your loved one can also feel your temperature. Let the hug not be a cold touch, but make the love more complete.

3.2. Neural interface technology

Neural interface technology for solving such problems includes invasive and non-invasive technology. In the realm of invasive technology, substantial advancements in the biocompatibility of implantable medical devices, minimally invasive microelectrodes for nerve signal detection, energy-efficient signal processing, and the wireless transmission of recorded data have greatly enhanced societal acceptance of neural prosthetics, thereby extending benefits to a larger population of individuals with disabilities [6]. Generating a voltage or an electric current is one way to stimulate nerves. These methods pass a specific electrical charge through an electrode to a designated area [7]. Maintaining a space of hundreds of microns between the silicone nerve jacket and the electrode surface minimises the deleterious effects of the two properties of fibrosis and silicone encapsulation on electrode performance. Ultimately, platinum-iridium wires were found to be resistant to the environment in the body and not cause an immune response [8]. This benefit is undoubtedly a significant step forward for invasive neural interfaces. It offers hope of overcoming the contradiction between neural interface electrodes and the body's immune response.

An experiment has shown that non-invasive sexual feedback enables upper limb amputees to identify and acquire objects with extremely high accuracy. This feedback mechanism delivers consistent and adequate sensory data essential for the perceptual identification of the target object, while also facilitating the non-invasive restoration of stable sensory feedback for the prosthetic limb [9]. Although invasive techniques provide a richer and more accurate experience of long-term sensory feedback, non-invasive methods offer greater safety. In addition, not all users will be willing to undergo further surgery, but may opt for non-invasive feedback techniques —i.e., non-invasive. In particular, various methods for providing sensory feedback in prosthetic limbs by non-invasive means now show promising research. Future research will likely focus on implementing a more straightforward, less painful feedback strategy [10]. Recent advancements in neural interface technology have generated significant anticipation regarding the swift progression of cortical-

controlled neuroprocessing. [11]. Regarding invasive and non-invasive prosthetics, I believe that non-invasive technology, which will be the focus of future research, is more friendly to prosthetic wearers. A high degree of safety is essential in the first place, not to mention that this technology is targeted at amputees. Moreover, non-invasive neural interface technologies do not require as many electrode patches to be attached to the body as invasive ones. They are more portable in daily life.

3.3. Biomimetic skin

Although the above methods are technically successful in solving the problem of artificial hand insensibility, their functionality is still limited, and they still pose significant challenges when performing everyday tasks, such as picking up fragile objects. The emergence of a smart myoelectric prosthetic hand with a bionic tactile sensor undoubtedly brings hope for solving such problems [12]. One of the basic functions of bionic skin is to provide tactile information. The bionic skin can be used to create prosthetics with sensory feedback and monitor a patient's medical condition. The optimal bionic integument should exhibit sensitivity, flexibility, and lightweight characteristics, while also possessing the ability to engage with the ambient environment[13]. Over the past few years, this technology has been used to stimulate the natural sensory perception of amputees. A researcher, Rossini et al., employed a methodology that facilitated amputees in experiencing tactile and paresthetic sensations in various regions of their phantom limbs. Additional researchers have corroborated analogous findings through alternative approaches [14].

4. Current challenges and prospects

Compared to invasive sensory feedback, non-invasive technology, while avoiding surgical risks and being easy to wear, still presents many challenges. Initially, the precision of feedback is suboptimal; the restoration of authentic tactile sensations is challenging, and potential signal latency may compromise real-time functionality. Furthermore, the comfort of non-invasive wear is inadequate; prolonged usage could result in dermal discomfort or inconsistent feedback. Moreover, most devices' durability and energy efficiency are limited, and the sensors are prone to ageing due to environmental influences. At the same time, some technologies can cause phantom limb pain in amputees, cognitive confusion, and, worse, privacy issues. Therefore, the future direction will be improving feedback accuracy, optimising user experience, and combining multiple technologies. Invasive electronic skin materials also face significant technical challenges. Today's rigid electronics don't fit the soft ergonomics. Incorporating electronic skin into a prosthetic requires a thin material that can bend and stretch without damaging its conductive properties. Not only that, but if the technology is to be used in real life, after making a material that meets this requirement, people need a device that can manufacture large quantities of this material and embed it in enough sensors to simulate it. But the current technology is still crude. Eventually, I believe that engineers will succeed in creating materials that will allow prosthetic limbs to feel, using electronic skin technology so that amputees can wear prosthetic limbs more comfortably and confidently .

5. Conclusion

It has been proven that each sensory feedback method has successfully provided different sensory feedback to prosthetic users with different technical techniques, and can restore their sensory function to a certain extent. However, most tests have been in the lab and have not yet been implemented in real life. Because each technology faces some degree of technical challenges. For

example, the current crude technology cannot be designed to fit the ergonomic electronic skin material fully. However, as the technology improves, they are expected to be widely used in the clinic, giving amputees a more natural and precise tactile experience.

References

- [1] M. F. Simons et al., ‘B: Ionic Glove: A Soft Smart Wearable Sensory Feedback Device for Upper Limb Robotic Prostheses’, *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 3311–3316, Apr. 2021, doi: 10.1109/LRA.2021.3064269.
- [2] Y. Wang et al., ‘Effective Evaluation of Finger Sensation Evoking by Non-Invasive Stimulation for Sensory Function Recovery in Transradial Amputees’, *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 30, pp. 519–528, 2022, doi: 10.1109/TNSRE.2022.3155756.
- [3] H. Fares et al., ‘Screen Printed Tactile Sensing Arrays for Prosthetic Applications’, in 2018 IEEE International Symposium on Circuits and Systems (ISCAS), May 2018, pp. 1–4. doi: 10.1109/ISCAS.2018.8351892.
- [4] L. Jabban, S. Dupan, D. Zhang, B. Ainsworth, K. Nazarpour, and B. W. Metcalfe, ‘Sensory Feedback for Upper-Limb Prostheses: Opportunities and Barriers’, *IEEE Trans. Neural Syst. Rehabil. Eng. Publ. IEEE Eng. Med. Biol. Soc.*, vol. 30, pp. 738–747, 2022, doi: 10.1109/TNSRE.2022.3159186.
- [5] S. Micera, ‘Material surface detection on various body parts: a preliminary study for temperature substitution for upper arm amputees’, in 2021 10Th International Ieee/Embs Conference On Neural Engineering (Ner), IEEE, Jan. 2021, pp. 195–198. doi: 10.1109/NER49283.2021.9441262.
- [6] J. Zhang, C. Chou, X. Wu, W. Pei, and N. Lan, ‘Non-Invasive Stable Sensory Feedback for Closed-Loop Control of Hand Prosthesis’, in 2022 44th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC), Jul. 2022, pp. 2344–2347. doi: 10.1109/EMBC48229.2022.9871682.
- [7] J. He, C. Ma, and R. Herman, ‘Engineering Neural Interfaces for Rehabilitation of Lower Limb Function in Spinal Cord Injured’, *Proc. IEEE*, vol. 96, no. 7, pp. 1152–1166, Jul. 2008, doi: 10.1109/JPROC.2008.922593.
- [8] L. Bisoni, C. Carboni, L. Raffo, N. Carta, and M. Barbaro, ‘An HV-CMOS Integrated Circuit for Neural Stimulation in Prosthetic Applications’, *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 62, no. 2, pp. 184–188, Feb. 2015, doi: 10.1109/TCSII.2014.2387679.
- [9] D. J. DiLorenzo, D. J. Edell, M. J. Koris, and R. R. Riso, ‘Chronic intraneural electrical stimulation for prosthetic sensory feedback’, in First International IEEE EMBS Conference on Neural Engineering, 2003. Conference Proceedings., Mar. 2003, pp. 116–119. doi: 10.1109/CNE.2003.1196770.
- [10] J. He, C. Ma, and R. Herman, ‘Engineering Neural Interfaces for Rehabilitation of Lower Limb Function in Spinal Cord Injured’, *Proc. IEEE*, vol. 96, no. 7, pp. 1152–1166, Jul. 2008, doi: 10.1109/JPROC.2008.922593.
- [11] Y. Li et al., ‘A review on carbon emission accounting approaches for the electricity power industry’, *Appl. Energy*, vol. 359, p. 122681, Apr. 2024, doi: 10.1016/j.apenergy.2024.122681.
- [12] T. Zhang, L. Jiang, and H. Liu, ‘Design and Functional Evaluation of a Dexterous Myoelectric Hand Prosthesis With Biomimetic Tactile Sensor’, *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 7, pp. 1391–1399, Jul. 2018, doi: 10.1109/TNSRE.2018.2844807.
- [13] A. Elsayes, A. Koivikko, and V. Sariola, ‘Tactile Electronic Skin Based on Conductive Fabric for Robotic Hand Applications’, in 2019 IEEE SENSORS, Oct. 2019, pp. 1–4. doi: 10.1109/SENSORS43011.2019.8956811.
- [14] M. M. Iskarous and N. V. Thakor, ‘E-Skins: Biomimetic Sensing and Encoding for Upper Limb Prostheses’, *Proc. IEEE*, vol. 107, no. 10, pp. 2052–2064, Oct. 2019, doi: 10.1109/JPROC.2019.2939369.