Advances and Challenges in Smart Prosthetics: A Review of Sensing, Actuation, and Bionic Design

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Abstract. Intelligent prosthetics signify a significant evolution from mechanical devices to advanced systems integrating mechatronics, biomedical engineering, and artificial intelligence. This review synthesizes recent technological advancements in key areas such as sensing and signal acquisition, actuation and execution, biomimetic structures and materials, feedback and perception, and energy management. Notable progress includes improving the accuracy of electromyographic signal classification through deep learning, developing hybrid actuation systems for enhanced power and efficiency, and fabricating multi-parameter electronic skins for high-fidelity tactile feedback. Despite these achievements, challenges remain in achieving stable signal acquisition, ensuring long-term usability and comfort, managing energy consumption, and, most crucially, reducing costs to improve accessibility. Future research must enhance reliability in real-world environments, improve user interaction, and make these advanced prosthetics affordable and accessible to the global amputee population.

Keywords: Smart Prosthetics, Mechatronic Integration, EMG Signal Processing.

1. Introduction

Nowadays, amputee patients are becoming more. According to the statistics of the World Health Organization, the total number of amputees worldwide is approximately 40 to 45 million (including both congenital and acquired amputations). Each year, there are 1.5 to 2 million new amputation cases [1]. Many of the amputations are because of diabetes mellitus, and a few of the amputations are due to accidents or congenital conditions. The “Smart prosthetics” is improved from pure machinery to a combination of mechatronics, biomedical engineering, and artificial intelligence.

The Smart prosthetics includes many different parts of technologies like sensing and signal acquisition technology, driving and Execution technology, artificial Intelligence and adaptive control, bionic structures and materials, feedback and perception technology, and energy and range-extending technology. For the Sensing and Signal Acquisition Technology, Ortega et al.’s study shows deep learning can improve the EMG signal classification accuracy by 15-20% compared to traditional identification methods [2]. For Drive and Execution Technology, Chen et al. [3] developed a novel hybrid actuator system combining shape memory alloys with pneumatic artificial muscles, achieving high power density and energy efficiency in prosthetic hands. For Feedback and Perception Technology, Shang et al. developed a biomimetic multi-parameter e-skin that resolved pressure, shear, and strain through stress field decoding, achieving 92.3% classification accuracy for basic tactile patterns via machine learning algorithms [4]. The Energy and Range-Extending Technology is a critical challenge addressed innovatively by Kim et al. through bio-inspired energy harvesting systems that convert kinetic energy to electrical power, extending battery life by up to 30% [5].

Although these technologies have succeeded, Bionic Structures and Materials, human-computer interaction, and connectivity still face significant challenges. Smart prosthetics are expensive, and few people can afford them. This review synthesizes many new smart prosthetic technologies and studies basic electromechanical components and technologies, their current applications, and future developments. We have focused on smart prosthetics in recent years with new techniques, and it’s a long-term challenge.

2. Sensing and Signal Acquisition Technologies

2.1 Electromyography (EMG)

Electrical signals from muscles are the electrical physiological signals generated when muscle fibers contract. It is the most important and mature signal source in intelligent prosthetic limb motion intention recognition technology. When the brain generates a movement intention and transmits it through the spinal cord motor neurons, the nerve endings release acetylcholine, causing the membrane of muscle cells to depolarize and generate action potentials. Many muscle fiber action potentials' temporal and spatial summation can be recorded on the skin surface as surface electromyographic signals (sEMG).

The System's constitution is the front end for signal acquisition. In recent years, flexible dry and textile electrodes have significantly progressed. In their review of laser-induced graphene (LIG) in 2023, Kothuru et al [6]. Systematically expounded that LIG, a cutting-edge laser processing technology, can rapidly and pattern-wise prepare porous graphene directly on various polymer substrates. The LIG electrodes made with it have awesome conductivity and mechanical flexibility, and can conform well to the skin. The fabricated LIG electrodes possess excellent electrical conductivity, mechanical flexibility, and the ability to achieve conformal contact with the skin. They can effectively adapt to skin deformation, maintaining stable interfacial impedance and high-quality signal acquisition even during motion. Zhao et al. developed a 3D knitted textile electrode with water retention properties [7]. This electrode features a unique yarn structure and knitting process, which can significantly reduce the electrode-skin interface impedance without using conductive gel. Keeping a small amount of moisture enables high-quality bio-electric signal acquisition during long-term use and movement, providing a more practical solution for the daily application of intelligent prosthetics.

2.2 Mechanical Sensing Technology

Mechanical sensors mainly measure the interaction force between the residual limb and the prosthesis's socket, providing supplementary information for control. The purpose of the Pressure/Sensor is to detect the posture and movement intention of the amputated limb.

Developing flexible electronic technology has enabled large-area and high-sensitivity pressure distribution sensing. Wang et al. developed a capacitive pressure sensor based on bionic-structured electrodes. Inspired by biological structures, the sensor features multi-level electrodes with microstructures, significantly improving the sensor's sensitivity, response speed, and stability [8]. This sensor is excellent for being embedded in prosthetic sockets to capture complex pressure distribution patterns, and it provides reliable mechanical information input for human-machine interaction applications. Besides capacitive sensing, other mechanical sensors like piezoresistive and piezoelectric sensors are also used in smart prosthetics. These sensors can measure different forces and vibrations, giving a more complete picture of how the prosthesis interacts with the environment. For example, some systems combine pressure data with inertial measurement units (IMUs) to better understand the user's motion and balance in real time. This multi-sensor approach makes the control system more intelligent and adaptive to different walking terrains or grasping tasks. Integrating these sensors into prosthetic liners and sockets also needs to consider comfort and durability, since they're in direct contact with the skin and need to work reliably day after day.

3. Mechanical Design in Smart Prosthetics

3.1 Bionic structure design

Modern smart prosthetic devices are no longer merely functional replacements; they are engineered to mimic human limbs' biomechanical structures and natural kinematics closely. Recent research emphasizes increasing the number of degrees of freedom (DoF) and improving the quality of movement, biocompatibility, and ergonomic integration with the user's body.

Current research on smart prosthetics has shifted from simple imitation to more complex biomimetic simulations. Wu et al developed a multi-phalangeal pneumatic soft dexterous finger. The multi-bone and joint structure of human fingers inspired the design. With an ultra-intelligent aerodynamic chamber layout and a framework restraint layer design, this finger can make those anthropomorphic bending movements of multiple knuckles with a single pneumatic input. It can copy the continuous and smooth grasping path of human fingers. It greatly increases the contact area with irregular objects and the stability of wrapping around them. This has provided a key module for building a full-soft bionic hand [9].

Furthermore, the structural compatibility between the prosthetic device and the human body is crucial. Recent designs often incorporate customizable, patient-specific socket interfaces using 3D scanning and printing technologies. These approaches improve weight distribution, reduce skin irritation, and enhance comfort during prolonged use.

3.2 Drive and Transmission Technology

The drive technology innovation aims to break the traditional trade-off between power, efficiency, and noise. Wu et al. demonstrated the unique advantages of pneumatic drive in soft bionic actuators for soft drive and pneumatic control. The multi-phalange soft finger they developed can control the bending posture of the whole finger just by adjusting the pressure of a single air source. The drive system is simple and doesn't need traditional gears and motors, which fundamentally solves the problems of noise and rigid impact and achieves a silent and safe drive [9]. Beyond pneumatic systems, alternative driving mechanisms such as shape memory alloys (SMAs), tendon-driven systems, and hydraulic actuators are also being investigated for specialized applications. SMAs, for example, offer high power density and silent operation but require sophisticated cooling strategies for cyclic operation. Tendon-driven systems provide precise force transmission and have been widely used in multi-fingered prostheses due to their biomimetic force transmission properties and compatibility with various attachment configurations.

Soft robotics technology represents a revolutionary approach to addressing human-machine safety interaction and comfort issues. Recent material advances include the development of self-healing elastomers, conductive hydrogels, and 3D-printed thermoplastic polymers with tunable stiffness gradients. These materials enable the creation of prosthetic devices that can withstand repetitive strain, maintain electrical connectivity under deformation, and provide customized mechanical compliance at different segments of the prosthetic limb. Furthermore, integrating sensory feedback elements within these soft matrices paves the way for closed-loop control systems that adapt to changing environmental conditions and user intentions.

For the soft prostheses represented by Wu et al., performance evaluation includes gripping force and range of motion and focuses on new indicators like interaction safety, success rate of adaptive grasping, and surface fit on different objects [9]. Moreover, long-term usability metrics are gaining increased attention. These include durability under cyclic loading, resistance to environmental factors (such as temperature and humidity variations), and maintenance requirements. Clinical evaluation parameters such as user adaptation time, learning curve characteristics, and subjective comfort ratings during extended wear are also becoming standard assessment criteria. These comprehensive evaluation frameworks ensure that soft prosthetic devices meet engineering excellence and practical user needs in real-world scenarios.

4. Challenges and Future Directions

Even though significant progress has been made, several challenges remain. The first is signal robustness: EMG signals are susceptible to noise, muscle fatigue, and motion artifacts caused by electrode shift. Power management is another critical issue, as energy consumption remains excessively high, particularly for advanced actuators and processing units. Cost and accessibility also present significant barriers; the prohibitively high expenses hinder widespread adoption. Another challenge lies in enhancing the real-time adaptability of these devices. For instance, prosthetics may not respond promptly when the user abruptly changes grip or traverses uneven terrain. Environmental conditions like rain or cold temperatures can further impact material integrity and electronic performance. Additionally, everyday exposures like sweat, dust, and physical shocks can interfere with sensor accuracy and degrade battery life.

Future research should prioritize long-term wear comfort and biocompatibility. Stability under complex environmental conditions (such as slippery surfaces) requires further improvement. Another crucial goal is to reduce the high costs associated with intelligent prosthetic limbs. Although advanced devices entail considerable expense, the ultimate objective is to make them accessible and affordable for all users. Therefore, cost reduction should be a primary focus after addressing technical hurdles. Efforts should also be directed toward simplifying the initial setup and user calibration process. Many existing devices still depend on professional installation and frequent recalibration, which limits practicality for non-specialist users. Streamlining the control system—through more intuitive software or self-adjusting algorithms—would significantly enhance usability. Moreover, refining bidirectional communication via improved feedback mechanisms, such as vibrotactile or subtle pressure cues, could promote greater embodiment and integration of the prosthetic.

5. Conclusion

Intelligent prosthetics integrate the achievements of multiple engineering disciplines—including mechatronics, biomedical engineering, artificial intelligence, and materials science—bringing amputees unprecedented capabilities in motion control, environmental interaction, and daily functionality. This review has systematically documented advancements across core areas such as high-precision EMG signal interpretation, hybrid and soft actuation systems, biomimetic mechanical design, and sensory feedback technologies, contributing to more natural, adaptive, and user-centered prosthetic solutions.

Despite these promising developments, significant challenges remain in achieving signal robustness under real-world conditions, managing high energy consumption, reducing costs, and ensuring long-term usability and comfort. Environmental adaptability, calibration complexity, and hardware durability under daily wear further complicate large-scale implementation and accessibility.

Looking forward, sustained progress in mechatronics, artificial intelligence, neuroengineering, and energy harvesting points toward a future where smart prosthetics are highly functional and intuitive to operate, affordable, reliable, and accessible to amputees worldwide. Interdisciplinary research and user-centric design will be essential to overcome existing barriers and realize prosthetics that restore natural movement and improve the quality of life across diverse populations.

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