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Artificial Intelligence in Prosthetics and Orthotics: Challenges, Opportunities and Clinical Implications

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Abstract

Artificial Intelligence (AI) is rapidly reshaping the field of prosthetics and orthotics by enhancing device design, control strategies, and clinical decision-making. Through advanced machine learning, neural networks, and pattern recognition algorithms, AI enables prosthetic and orthotic systems to interpret bio signals, predict user intent, and adapt in real time to changing environments. These innovations contribute to more natural limb control, improved gait efficiency, and personalized rehabilitation strategies. Moreover, AI-driven computer vision and gait analysis tools support clinicians in patient assessment, socket or orthosis design, and outcome prediction, thereby improving the precision and efficiency of care. Despite these opportunities, significant challenges remain. Data scarcity in amputee populations, high device costs, variability in performance across users, and limited large-scale clinical validation hinder widespread implementation. Ethical considerations such as data privacy, algorithmic transparency, and equitable access further complicate integration into routine clinical practice. Nevertheless, ongoing research into multimodal sensing, brain-computer interfaces, adaptive orthotic control, and AI-assisted digital workflows shows great promise for advancing patient cantered solutions. This paper discusses the challenges, opportunities, and clinical implications of AI in prosthetics and orthotics, emphasizing its potential to transform rehabilitation practices and redefine standards of mobility and independence in the near future.

Keywords: Artificial Intelligence (AI), Prosthetics, Orthotics, Brain-computer Interface (BCI)

1. Introduction

Prosthetics and orthotics (P&O) play a critical role in restoring function, mobility, and independence for individuals with limb loss or neuromusculoskeletal impairments. Traditional devices, although effective, are often limited by mechanical design constraints, lack of adaptability, and reliance on manual clinical expertise for alignment and adjustment. In recent years, Artificial Intelligence (AI) has emerged as a transformative technology in the P&O field, providing new opportunities to improve device control, design, and rehabilitation outcomes [1,2].

AI techniques such as machine learning, deep learning, and neural networks allow prosthetic and orthotic systems to interpret bio signals—such as surface electromyography (SEMG), electroencephalography (EEG), and kinematic data—for predicting user intent and enabling intuitive, real-time control [3,4]. For example, in upper-limb prostheses, AI-driven pattern recognition improves the accuracy and responsiveness of myoelectric hands, facilitating more natural grasping and manipulation. Similarly, in lower-limb prostheses and robotic orthoses, AI supports gait phase detection, terrain recognition, and adaptive control, leading to safer ambulation and reduced energy expenditure [5].

Beyond device control, AI is also being applied in design and clinical decision-making. Algorithms can analyse patient data to optimize socket rectification, predict rehabilitation outcomes, and support clinicians in selecting appropriate components. Computer vision–based gait assessment further enables remote monitoring and outcome tracking, reducing the dependency on laboratory infrastructure [6].

Despite these opportunities, several challenges hinder the clinical translation of AI in P&O. These include the scarcity of large, high-quality datasets from amputee populations, variability of performance across users, high costs of AI-enabled devices, and the lack of standardized clinical validation protocols [7]. Ethical and practical considerations such as algorithmic transparency, data privacy, and equitable access also raise important concerns for healthcare integration.

Given these challenges, yet recognizing the rapid pace of innovation, it is essential to critically examine the opportunities and clinical implications of AI in P&O. This paper reviews the current state of AI applications in prosthetics and orthotics, highlights the barriers to adoption, and discusses the potential of AI to redefine rehabilitation practices, device personalization, and patient quality of life.

2. Types of AI Used in Prosthetics and Orthotics

2.1 Machine Learning (ML)

Machine learning algorithms, including support vector machines (SVM), k-nearest neighbors (k-NN), and decision trees, are widely applied in P&O. These models are particularly effective in pattern recognition of EMG signals, which allows prosthetic limbs to detect user intent and map it to specific movements.

2.2 Deep Learning (DL)

Deep learning techniques such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs) have shown superior performance in multimodal signal processing. CNNs are used in image-based gait analysis and socket design, while RNNs handle time-series bio signals for continuous intent prediction.

2.3 Reinforcement Learning (RL)

Reinforcement learning is prominent in orthotic and exoskeleton systems. By continuously interacting with the user and environment, RL algorithms optimize assistance levels in real time, promoting natural gait patterns and reducing patient fatigue.

2.4 Brain–Computer Interfaces (BCI) with AI

AI-enhanced BCIs decode neural activity, allowing direct control of prostheses. This technology holds promise for high-level amputees and individuals with severe motor impairments, where traditional EMG-based systems are insufficient.

2.5 Hybrid AI Systems

Combining multiple approaches, such as ML with computer vision or RL with EMG decoding, hybrid systems enhance robustness and adaptability in real-world environments.

3. Mechanism of Artificial Intelligence an Prosthetics And Orthotics

The integration of Artificial Intelligence (AI) in prosthetics and orthotics (P&O) relies on a systematic mechanism that transforms biological and mechanical data into meaningful control signals, adaptive responses, and clinical decision support. This mechanism can be broadly divided into four stages: data acquisition, signal processing, machine learning interpretation, and real-time application in devices.

The data acquisition mechanism begins with the collection of bio signals and biomechanical data from the user. Surface electromyography (SEMG), electroencephalography (EEG), and mechanomyography (MMG) are commonly used to capture neuromuscular activity, while inertial measurement units (IMUs), force sensors, and pressure sensors provide gait and kinetic information [4,5]. High-resolution motion capture and wearable sensors further complement data acquisition, ensuring that user intention and biomechanical states are captured with precision.

Raw bio signals are often noisy and require preprocessing, including filtering, normalization, and segmentation. AI models then extract discriminative features such as amplitude, frequency, and temporal patterns. For example, SEMG signals are analyzed for muscle activation patterns that correspond to specific motor intentions [1]. Feature extraction ensures that only meaningful data is passed to the AI model, enhancing accuracy and efficiency.

At this stage (AI-Based Interpretation and Decision-Making), machine learning and deep learning algorithms-including neural networks, support vector machines, and reinforcement learning-interpret user intent. In prosthetics, these algorithms classify hand gestures, gait phases, or locomotion modes, enabling seamless control of robotic limbs [3]. In orthotics, AI-driven models adapt device stiffness, torque, or assistance levels in real time based on the user's gait and posture [7]. Importantly, reinforcement learning enables devices to continuously refine their responses through user feedback, promoting personalized adaptation.

Finally, the interpreted signals are transmitted to prosthetic or orthotic actuators. In upper-limb prostheses, this allows intuitive grasp, pinch, or rotation control, while in lower-limb prostheses and exoskeletons, AI mechanisms coordinate joint actuation for smoother walking across varied terrains [5]. Cloud-based AI further enhances this mechanism by enabling remote rehabilitation monitoring, predictive maintenance, and adaptive training protocols.

Collectively, the mechanism of AI in P&O creates a closed-loop human–machine interface, where real-time data continuously informs adaptive device responses. This dynamic interaction not only improves functional outcomes but also enhances user comfort, safety, and quality of life.

4. Challenges of Using Artificial Intelligence in Prosthetics and Orthotics Field

The integration of Artificial Intelligence (AI) into prosthetics and orthotics (P&O) has brought significant advancements in device functionality, personalization, and clinical outcomes. However, several technical, clinical, ethical, and socio-economic challenges hinder the widespread adoption of AI-based solutions in this field.

AI systems depend heavily on high-quality, diverse, and standardized datasets for training. Collecting large-scale bio signal datasets such as surface electromyography (SEMG), EEG, and gait patterns is difficult due to inter-patient variability, noise, and ethical concerns regarding patient data privacy [1]. Moreover, the absence of global databases for amputees or individuals with musculoskeletal disorders limits the generalizability of AI algorithms.

AI-driven prostheses and orthoses require real-time interpretation of bio signals to ensure seamless interaction between the device and the user. However, signal processing and deep learning algorithms often demand high computational power and energy, which is challenging for wearable devices with limited battery capacity [4]. Achieving low-latency performance while maintaining accuracy remains a key obstacle.

AI algorithms often struggle to generalize across different populations due to variations in muscle physiology, amputation levels, residual limb conditions, and user training. For instance, an algorithm trained on one group of users may not perform effectively when applied to another [1]. This necessitates time-consuming individual calibration and retraining, reducing clinical efficiency.

The effectiveness of AI depends on reliable input from sensors. However, sensors used for capturing bio signals (e.g., SEMG electrodes) are prone to displacement, sweat interference, and electrical noise, leading to misclassification of user intent [5]. Additionally, integrating AI algorithms into compact, lightweight, and energy-efficient hardware platforms remains a significant engineering challenge.

The clinical use of AI raises issues of data security, informed consent, and algorithmic transparency. Black-box models, such as deep neural networks, often lack interpretability, making it difficult for clinicians to understand or explain device decisions [2]. Furthermore, there is a lack of standardized regulatory frameworks to evaluate and approve AI-enabled prosthetic and orthotic devices, delaying their translation from research to practice.

AI-based prosthetic and orthotic devices are often expensive due to advanced sensors, embedded processors, and machine learning integration. This cost restricts accessibility, particularly in low-resource settings, where the majority of individuals with disabilities reside (World Health Organization [WHO], 2017). Without affordable and scalable solutions, the benefits of AI may remain limited to high-income countries.

5. Advantages and Opportunities of Artificial Intelligence in the P&O Field

The integration of Artificial Intelligence (AI) into prosthetics and orthotics (P&O) presents remarkable advantages and transformative opportunities for patient care. AI-driven systems enable personalized rehabilitation, allowing devices to adapt to individual biomechanics and user intent in real time, thereby improving mobility and functionality [4]. Machine learning algorithms enhance the accuracy of movement prediction and control, leading to smoother gait patterns and more natural limb movements in prosthetic users [3]. In orthotics, AI facilitates data-driven customization, using gait analysis, pressure mapping, and predictive modelling to design supportive devices that optimize comfort and reduce secondary complications. Additionally, AI offers opportunities for remote monitoring and tele-rehabilitation, increasing accessibility of advanced P&O services in resource-limited regions (WHO, 2017). Importantly, innovations such as human-in-the-loop optimization and brain–computer interface integration hold the potential to make prostheses and orthoses more intuitive and responsive, reshaping rehabilitation practices for the future. Collectively, these advancements position AI as a catalyst for a more efficient, inclusive, and patient-centered P&O field.

6. Results and Discussion

Studies indicate that AI-driven prostheses can achieve up to 95% accuracy in user intent recognition using advanced EMG pattern recognition and deep learning models [1]. AI-enhanced powered knee prostheses demonstrated smoother transitions between walking, climbing, and sitting, improving safety and reducing falls [3]. In orthotics, reinforcement learning-based exoskeletons improved rehabilitation outcomes by providing adaptive support, encouraging active participation from patients [2].

Despite these advances, challenges persist in real-world deployment, where uncontrolled environments introduce variability. Clinical adoption remains slow due to cost, limited large-scale validation, and regulatory hurdles. However, ongoing research into multimodal AI systems, brain–computer interfaces, and cloud-based rehabilitation tools highlights a promising future for P&O. The clinical implications are profound, as AI-driven devices could redefine standards of mobility, independence, and quality of life.

Future Scope of Study:

The future of Artificial Intelligence in prosthetics and orthotics lies in developing systems that are more intelligent, affordable, and clinically scalable. Brain–computer interfaces combined with AI may provide seamless communication between the nervous system and assistive devices, especially for high-level amputees and individuals with severe motor impairments. Similarly, cloud-based and edge-computing platforms could enable real-time data processing, remote monitoring, and personalized rehabilitation through telehealth integration.

Another promising direction is the creation of low-cost AI-driven devices tailored for low- and middle-income countries, ensuring equitable access to advanced rehabilitation technologies. Hybrid systems that integrate bio signals, gait kinematics, and computer vision will further improve robustness in uncontrolled environments. As ethical frameworks mature, AI in P&O will likely shift toward humancentered, inclusive innovation, ensuring not only technical advancement but also social impact. With continued interdisciplinary collaboration, AI-enabled prosthetics and orthotics are poised to transform rehabilitation into a more adaptive, accessible, and personalized domain.

7. Conclusion

Artificial Intelligence has immense potential to revolutionize prosthetics and orthotics by enhancing control, adaptability, and clinical decision-making. While challenges such as cost, data scarcity, and ethical concerns remain, the opportunities for personalized, patient-centered care are vast. Future research must focus on bridging the gap between laboratory innovation and clinical practice, ensuring that AI-driven P&O solutions are accessible, reliable, and equitable for all patients.

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