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Application of Artificial Intelligence in Prosthetics: A Review

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Abstract— *This review paper explores the application of artificial intelligence (AI) in advanced prosthetic devices, including limbs, retinal prosthetics, hearing prosthetics, and ortho dental prosthetics, with the aim of enhancing functionality and customization. The research problem centers around understanding AI's forthcoming impact on prosthetic advancements. The study's objectives are twofold: to identify current AI applications in prosthetics and to project future possibilities. The paper uses qualitative secondary analysis to review existing research. By leveraging AI algorithms, prosthetic limbs can interpret nerve signals derived from the patient's muscles, resulting in more precise control and operation. AI-driven advancements include myoelectric prostheses that utilize electromyography signals, bionic legs that adapt to different environments based on user feedback, and prosthetic arms capable of executing actions using computer vision recognition. Additionally, AI improves retinal prosthetics by combining neural networks with computer vision techniques to refine facial features, enhance environmental representation, and ensure safety. In hearing prosthetics, AI, machine learning, and neural networks enable devices to adapt to individual hearing needs and background noise environments. AI-based object detection techniques streamline dental implant surgery in ortho dental prosthetics. The integration of AI in prosthetic devices holds the potential to enhance functionality, improve control and customization, and provide a more natural user experience, benefiting millions worldwide with limb amputations, vision and hearing impairments, and dental prosthetic needs.*

Keywords— **Prosthetics, Artificial Intelligence, Machine Learning, Neural Networks, Retinal Prosthetics, Hearing Prosthetics, Dental prosthetics**

I. INTRODUCTION

A prosthetic is a remarkable device that serves as a substitute or supplement for a missing or defective part of the body, either externally or through implantation (Worrell, n.d.). Over the years, significant advancements in the field of prosthetics have been made, with artificial intelligence (AI) emerging as a transformative technology that has the potential to revolutionize the functionality and control of prosthetic devices. By leveraging AI algorithms and deep learning techniques, prosthetics can now offer individuals with limb amputations or impairments the opportunity to regain natural movement and seamless interactions with their prosthetic limbs ("The Man-Machine Interaction: The Influence of Artificial Intelligence on Rehabilitation Robotics," n.d.) .Deep learning, a subset of machine learning and AI, plays a significant role in advancing prosthetic technology. It utilizes artificial neural networks (ANN) with representation learning, drawing inspiration from the dynamic and analogy nature of the human brain's neural network system. Deep learning algorithms employ supervised and unsupervised learning methods, allowing prosthetic devices to adapt, learn, and respond in a manner that closely mimics natural human movements. The use of neural networks in rehabilitation aids has revolutionized the field, leading to the development of devices like bionic legs, mind-controlled prostheses, and exoskeletons. These advancements, integrating human interaction with electronic circuitry, software, and robotics, have greatly improved the quality of life for individuals with disabilities.

The main objective of this research is to comprehensively study and analyse the current AI-integrated prosthetic devices, aiming to comprehend the underlying technologies employed and their transformative impact on this field, ultimately enhancing natural functionality. This review paper presents a condensed analysis of diverse technologies utilized across various types of prosthetics, catering to limb, hearing, vision, and oral functionalities. By advancing prosthetic designs that prioritize user-friendliness, practicality, and seamless integration into users' daily lives, the trajectory of AI in prosthetics stands poised to revolutionize the profession. Anticipated advancements in artificial intelligence, neuroscience, and materials science are expected to culminate in the creation of a novel generation of prosthetics, reinstating not solely physical capabilities but also fostering an innate sense of organic motion and command.

II. LITERATURE REVIEW

Between 10 and 15 million people worldwide have amputations(Chopra, 2022). György Lévay, a Research Manager of Infinite Biomedical Technologies, states how A.I. will be a part of advanced prostheses in the future in one way or the other. He also states how more advanced algorithms will be needed to handle the increasing volume of data transmitted between our brain and limb as technology develops("The Future Of Prosthetics Depends On A.I.," 2020). The integration of artificial intelligence in robotic prostheses aims to enhance their functionality by leveraging algorithms to interpret nerve signals derived from the patient's muscles. This allows for more precise control and operation of the prosthesis. The components of the prosthesis encompass terminal devices like artificial fingers, hands, feet, and toes, as well as joints including wrists, elbows, hips, and knees(Chopra, 2022). By utilizing AI, human-machine peripheral interfaces can be developed to improve the seamless functioning of these prosthetic devices.

I. Prosthetic Limbs (Arms and Legs)

According to a study conducted in 2017, it was estimated that there were approximately 57.7 million individuals worldwide living with limb amputations. Chas. A. Blatchford & Sons of Great Britain introduced the first commercially available microprocessor-controlled prosthetic knee, called the Intelligent Prosthesis, in 1993. It improved the natural look and feel of walking with a prosthetic. An upgraded version, the Intelligent Prosthesis Plus, was released in 1995. In 1998, Blatchford also introduced the Adaptive Prosthesis, which utilized hydraulic and pneumatic controls along with a microprocessor. Computerized knees are a newer type of prosthetic technology. They learn the user's walking characteristics and have sensors to measure timing, force, and swing. This data is used to adjust the fluid control system, resulting in a more natural gait, increased endurance, and better control on uneven surfaces. They are suitable for active amputees (Chopra, 2022).

Myoelectric prostheses, which are widely available advanced artificial limbs, rely on electromyography (EMG) signals from the remaining muscles of the amputated limb for control. To control these prosthetics, sensors are placed on the skin above the residual limb muscles. When the user contracts these muscles, the sensors interpret the signals as electrical impulses, which are then converted into commands that dictate the movement of the prosthetic limb. Tasks such as overcoming obstacles, walking on uneven surfaces, or navigating stairs can pose difficulties for individuals using prosthetic legs. Researchers at the University of Utah, specializing in mechanical engineering, have taken measures to simplify these common tasks. They have developed a bionic leg that utilizes artificial intelligence (AI) and machine learning to adapt to different environments based on feedback from the user's remaining limb. By placing sensors on the hip muscles of the residual limb, the bionic leg determines the user's intended movement and uses AI to flex the prosthetic knee and adjust the duration of its swinging motion accordingly. Moreover, the leg can also adapt to the user's specific walking pattern, resulting in effortless and more natural movement for the individual ("How AI is Helping Power Next-Generation Prosthetic Limbs," 1674464232639).

A team of researchers from the University of Michigan introduced a novel approach to expand the application of technology to various types of prostheses. Their innovative method, which involves utilizing a regenerative peripheral nerve interface (RPNI), requires surgeons to take a small muscle segment and wrap it around the severed nerve end to enhance the signals. Subsequently, computational scientists on the team employ machine learning algorithms to translate these signals into precise movements within a prosthetic device. An intriguing aspect of this surgical technique is its versatility, as it is effective for any type of amputation. Artificial intelligence (AI) is being employed to grant prosthetic arms the capability to independently execute actions like finger movements. As an illustration, a group of researchers from Newcastle University developed a prosthetic hand in 2017 that utilizes computer vision to recognize the object it intends to grasp. It then automatically adjusts its grip without requiring manual intervention from the user ("The Future Of Prosthetics Depends On A.I.," 2020)

Through the utilization of emerging recognition technologies, a person can operate a robotic hand in a manner that closely resembles how they would control their original hand. This is particularly crucial for individuals with limb amputations, as their brains undergo cortical reorganization following the amputation, resulting in the phenomenon known as phantom pain ("The Man-Machine Interaction: The Influence of Artificial Intelligence on Rehabilitation Robotics," n.d.)To enhance the performance of prostheses, the evaluation of feedback responses can be carried out using PID algorithms (Proportional-Integral-Derivative algorithm). This enables us to effectively address response time and steady-state errors. Moreover, the utilization of pattern recognition techniques proves to be highly beneficial in achieving more realistic or semi-realistic hand movements (Alshamsi et al., 2016).

In a publication in the journal Nature, researchers from the Massachusetts Institute of Technology, explained how the utilization of deep learning has facilitated the creation of an affordable tactile glove. This glove has the ability to identify objects, estimate the weight of unfamiliar objects, and differentiate between various hand positions. If further advancements are made, this technology could potentially be integrated into active prostheses and robotic hands ("Human–robotic interfaces to shape the future of prosthetics," 2019)

Prosthetics can be developed using a BCI System (Brain-Computer Interface) which uses AI. A BCI system enables individuals to interact with automated systems, such as robotic arms or prosthetic arms, by utilizing their brain activity instead of relying on muscular control. The core idea behind a BCI is to translate patterns of brain activity generated by the user into corresponding commands ("Design and Implementation of Smart Prosthetic Hand Using Artificial Intelligence," n.d.)The peripheral nerve interface is a more efficient replacement for EMG-controlled prosthetic limbs. Instead of using sensors on the skin, it relies on implanted electrodes to read signals directly from the nerves.

Researchers from the University of Minnesota have developed an AI system to decode these signals. Training the AI involves wearing a data glove and performing hand movements on both the intact and amputated arms. The AI learns to correlate nerve signals with specific hand movements and can recognize multiple movements simultaneously, such as pinching ("How AI is Helping Power Next-Generation Prosthetic Limbs," 1674464232639)

Researchers have also developed methods to create speech-controlled prosthetic hands, employing convolutional neural networks (CNNs). CNNs are utilized to analyze and search lookup tables, enabling the prosthetic hands to be guided based on spoken commands.(Jafarzadeh and Tadesse, 2019)

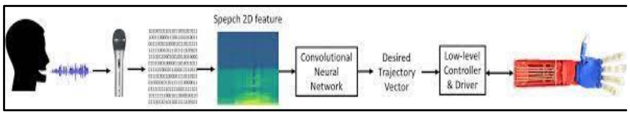

Figure 4: Block diagram of controlling prosthetic hands via speech recognition system.

Source: (Jafarzadeh and Tadesse, 2019)

The collection of data from amputees holds great value in enhancing the performance and customization of prosthetic devices. Presently, the process of measuring gait and refining a leg prosthesis necessitates regular visits to a specialist over an extended period. However, an intelligent leg prosthesis capable of capturing data during everyday activities and using that data as a reference for making adjustments would be an ideal solution. By continuously gathering data and adapting the technology to suit the individual's requirements and preferences, the prosthetic device can be customized more effectively, resulting in an improved user experience (Worrell, n.d.).

The concept of an EEG-based mind-controlled smart prosthetic arm was introduced at the 2016 IEEE conference. However, to date, this concept has not been commercialized. Researchers are currently working towards the development of more sophisticated devices that emulate the natural brain. These devices incorporate artificial intelligence into on-board computers, enabling them to interpret and respond to nerve signals transmitted to robotic prostheses and orthoses. This advancement aims to enhance the functionality of amputated and paralysed body parts ("Application of Artificial Intelligence (AI) in Prosthetic and Orthotic Rehabilitation | IntechOpen," n.d.)

J. Retinal Prosthetics

Retinal prosthetics aim to restore functional vision to the millions of individuals worldwide who suffer from diseases that lead to the deterioration of vision. Researchers have made significant improvements in retinal prosthetics (RP) by combining neural networks (NNs) with computer vision (CV) techniques. By incorporating NNs into CV algorithms, they have been able to refine facial features, enhance environment representation, and minimize collisions through hazard detection. These advancements have contributed to the overall improvement of RP systems, enhancing their effectiveness and safety (Perala, n.d.). Retinal prosthesis may eventually learn from user interactions and adapt through AI algorithms. As the device fine-tunes its responds according to the user's preferences and feedback, this could result in greater performance and satisfaction for the user.

K. Hearing Prosthetics

Hearing prosthetics are devices used to assist individuals with hearing impairments, and the technology employed in these prosthetics is already significantly advanced in terms of functionality compared to other prosthetic devices. According to Professor Panahi, an expert in electrical and computer engineering, hearing aids must possess the ability to adapt to an individual's specific hearing needs and various background noise environments in order to function effectively. To tackle the complexity of this challenge, which involves nonlinearity and multiple variables, he highlights the effectiveness of utilizing techniques such as AI, machine learning, and neural networks (“Hearing aids go high-tech,” 2021). Essentially, the implementation of a deep neural network (DNN) enables hearing aids to replicate how a healthy brain perceives sound, thereby compensating for hearing impairments (“New generation intelligent hearing prosthetics,” n.d.). AI-powered hearing prosthetics could intelligently adjust their settings based on the listening environment. They could automatically switch between modes for noisy environments, quiet settings, music appreciation, and more, enhancing the user's comfort and engagement.

L. Ortho dental Prosthetics

Artificial intelligence in implantology has the potential to merge and revolutionize the field, paving the way for future prosthetics (Chau et al., 2022). A novel model that can accurately and automatically find the mandibular canal for dental implant surgery has been developed by researchers from The Alan Turing Institute, Planmeca, and the University Hospital of Tampere. By utilizing deep learning-based object detection on panoramic radiography images, implant systems can be identified with accuracy and efficiency. In the journal of Oral facial Rehabilitation it states how the researchers aimed to create a non-invasive, precise, and self-contained tongue-computer interface to assist severely disabled individuals who lack hand and arm functions (Awani Gupta et al., 2023)

III. RELATED WORKS

This section provides an overview of various prosthetic systems discussed in the previous section. It presents a condensed understanding of the technologies, methodologies, and limitations associated with these systems.

Table 1: Existing AI involved prosthetic systems.

No	System	Methodology	Limitations
1	Speech-controlled prosthetic hands	CNNs are employed to examine and explore lookup tables, allowing prosthetic hands to be directed using spoken instructions.	It relies solely on spoken commands for guiding the prosthetic hands
2	BCI controlled prosthetics (Vilela and Hochberg, 2020)	BCIs translate brain activity into commands for controlling devices or effectors.	Challenge of decoding high-dimensional and real-time control commands from the user's neural activity
3	EEG-based mind-controlled smart prosthetic (Beyrouthy et al., 2017)	The arm is equipped with a network of smart sensors and actuators that give the patient intelligent feedback about the surrounding. environment and the object in contact	Requirement for long training sessions to build a user-dependent library of brain activity patterns
4	Tactile glove developed by MIT (“Sensor-packed glove learns signatures of the human grasp,” 2019)	The system uses sensors to capture pressure signals, which are processed by a neural network to classify objects and predict their weights based on touch alone, without visual input.	Neglects other important sensory cues such as temperature, texture, and vibration, which humans rely on for a comprehensive understanding of objects
5	Argus II Retinal Prosthesis System	The process involves combining perceptual thresholds with electrode impedance measurements to create	Need for individualized lookup tables for each subject

		individualized lookup tables for each subject.	
6	Widex's Moment hearing aid	AI and machine learning are employed to generate customized hearing programs by analyzing the typical environments in which the wearer is present.	The hearing aid's reliance on analyzing typical environments may limit its adaptability and effectiveness
7	Oticon More	The first hearing aid equipped with an on-board deep neural network. Through training with over 12 million real-life sounds, it enables wearers to improve their comprehension of speech and the surrounding sounds.	Potential for limited generalizability
8	Tongue drive system (TDS)	Track tongue movements within the mouth and interpret commands according to predefined guidelines	Potential difficulty in achieving precise and consistent control.

Source: Author

IV.DISCUSSIONS

The study of existing systems and emerging technologies in the field of prosthetic development highlights the transformative potential of artificial intelligence (AI). With ongoing projects in development, the future of prosthetics is promising, but it also presents both advantages and disadvantages. In a recent announcement, Elon Musk unveiled Neuralink's endeavour to create a brain-machine interface, an implantable wireless device aimed at achieving symbiosis with AI. While the short-term applications of this technology focus on treating conditions like Parkinson's disease, Musk envisions a future where humans can keep pace with AI. Incorporating AI into the prosthetic development process holds promise for restoring fine motor control to amputees, but challenges remain. Weak control signals and the need for complex and expensive intramuscular electromyography (iEMG) sensors hinder the widespread usability of robotic prosthetic and neural interface (RPNI) systems. Overcoming these limitations requires further research and innovation to enhance signal strength, sensor technology, and cost-effectiveness. Addressing these limitations necessitates continued research and innovation. Efforts must be directed towards enhancing the strength of control signals, refining sensor technology, and optimizing cost-effectiveness. Collaborative endeavours between AI experts, biomedical engineers, and prosthetics specialists could pave the way for breakthroughs in this area. Developing more advanced and user-friendly sensor technologies, such as non-invasive EMG sensors or alternative neural interface techniques, could make AI-driven prosthetics more accessible to a broader population. By addressing these challenges, AI-driven prosthetics can significantly improve the quality of life for individuals with amputations.

V. CONCLUSION

In conclusion, the integration of artificial intelligence (AI) in advanced prosthetic devices has the potential to revolutionize the field of prosthetics by enhancing functionality, control, and customization. This review paper demonstrates how AI can be used to interpret nerve signals for accurate limb control, improve retinal prosthetics using neural networks and computer vision, customise hearing aids to each user's needs using AI and neural networks, and speed up dental implant surgery using deep learning-based object detection. Although these developments have the potential to improve people's lives all across the world, issues with signal accuracy and cost-effectiveness highlight the necessity of continued research and innovation. AI application in prosthetics and orthotics is in its early stages and not widely practiced. Many AI projects in this field are still prototypes and not commercialized. High costs of these devices limit accessibility for individuals with disabilities. Further research and innovation are necessary to overcome these challenges and unlock the full potential of AI in prosthetic development. (xyz, 2000). This evolving synergy of AI and prosthetics embodies a future where technology blurs the line between limitations and boundless human potential.

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