Robotics Used in Prosthetics & Orthotics

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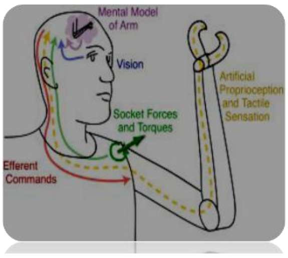
Abstract: ***Advancements in robotics have revolutionized prosthetics and orthotics, significantly enhancing functionality, user comfort, and quality of life. In prosthetics, robotic technologies such as myoelectric control systems, microprocessor - driven joints, and sensory feedback mechanisms enable intuitive and precise movements, mimicking natural limb function. Devices like bionic hands and adaptive prosthetic knees utilize sensors, actuators, and machine learning to interpret user intent and adapt to dynamic environments. In orthotics, robotic exoskeletons and active orthoses provide powered assistance, improving mobility for individuals with musculoskeletal impairments. These systems integrate lightweight materials, real - time control algorithms, and AI - driven personalization to optimize gait and reduce energy expenditure. Despite progress, challenges remain, including high costs, battery life limitations, and the need for improved sensory integration. This paper explores the current state of robotics in prosthetics and orthotics, highlighting key technologies, clinical applications, and future directions for accessible, user - centric assistive devices.***

Keywords: robotic prosthetics, myoelectric systems, adaptive orthotics, assistive exoskeletons, user - centered technology

1. Introduction

The use of prosthetics and orthotics has long served as a critical intervention for individuals with limb loss or musculoskeletal impairments, offering both functional restoration and psychological benefits. Prosthetic devices, by concealing amputations, can shield users from social stigma, fostering emotional healing and social reintegration. For individuals with disabilities, the struggle to regain limb functionality is often compounded by physical and emotional challenges. Robotic technologies have emerged as transformative solutions, enhancing the capabilities of prosthetic and orthotic devices to provide more natural, adaptive, and user - centric functionality. Defined as reprogrammable, multifunctional manipulators designed to move materials, parts, tools, or specialized devices through variable programmed motions (Robot Institute of America, 1980), robots in the context of prosthetics and orthotics are mechatronic systems classified as assistive robotics. These systems integrate sensors, actuators, and advanced control algorithms to mimic or augment human movement, offering unprecedented levels of precision and adaptability. For instance, myoelectric prosthetics translate muscle signals into complex movements, while robotic exoskeletons assist in gait rehabilitation for orthotic users (Hussain et al., 2021). This paper explores the role of robotics in prosthetics and orthotics, emphasizing their potential to address both physical and emotional needs of individuals with disabilities, while highlighting key technological advancements and their implications for future development.



Types of Robots Used in Prosthetics and Orthotics

Robotic technologies have revolutionized prosthetics and orthotics, offering advanced solutions to enhance mobility, functionality, and emotional well - being for individuals with limb loss or musculoskeletal impairments. Myoelectric prosthetic robots, such as Ottobock's Michelangelo Hand and Össur's Power Knee, utilize electromyography (EMG) sensors to detect muscle signals, enabling precise control of multi - articulated limbs for tasks like grasping or walking (Hargrove et al., 2017). Microprocessor - controlled prosthetics, like the C - Leg by Ottobock, employ sensors and adaptive algorithms to adjust joint movements in real - time, optimizing gait on varied terrains (Sawers & Hafner, 2016). Robotic exoskeletons, used in both prosthetics (e. g., ReWalk Personal Exoskeleton) and orthotics (e. g., EksoNR by Ekso Bionics), integrate lightweight materials and AI - driven gait prediction to assist or augment movement, benefiting paraplegic individuals or those in rehabilitation (Awad et al., 2017). Neural interface - controlled prosthetics, such as the Modular Prosthetic Limb, leverage brain - computer or peripheral nerve interfaces to translate neural signals into complex movements, though invasive methods pose challenges (Collinger et al., 2013). Active orthotic robots, like the HAL by Cyberdyne or Atalante exoskeleton by Wandercraft, provide powered joint assistance for neurological or elderly patients, enhancing stability and reducing fatigue (Gorgey et al., 2021). These robotic systems, by mimicking natural movement and concealing physical impairments, not only restore functionality but also mitigate social stigma, supporting emotional healing. Continued advancements aim to address limitations like cost and battery life, promising greater accessibility.

2. Major Advancement of Prosthetics Over Past 20years

Over the past two decades, the field of prosthetics and orthotics has seen remarkable advancements, transforming assistive devices into highly functional, intuitive systems that align with the Artificial Limb Program's 1945 vision of enhancing amputee mobility and quality of life, as established by the National Academy of Sciences. Innovations in prosthetic materials, such as lightweight carbon fiber, titanium, and 3D - printed polymers, have replaced heavy, rigid designs, enabling greater comfort, durability, and energy efficiency for users engaging in activities like running or daily tasks (Blaya et al., 2019). Bluetooth integration, introduced in the mid - 2000s, has enabled wireless communication in devices like Ottobock's Genium X3 knee, allowing users and clinicians to adjust settings in real - time via smartphones, enhancing adaptability and personalization. Microprocessor - controlled knees, such as the C - Leg, utilize sensors and algorithms to dynamically adjust to terrain and gait, improving stability and reducing fall risks for above - knee amputees (Sawers & Hafner, 2016). Myoelectric technology has advanced significantly, with electromyography (EMG) sensors translating muscle signals into precise movements in devices like the Michelangelo Hand, supported by machine learning for intuitive control (Hargrove et al., 2017). Targeted muscle reinnervation (TMR), developed in the early 2000s, reroutes nerves to alternative muscles, enhancing myoelectric signal clarity and enabling complex prosthetic functions, while also reducing phantom limb pain (Dumanian et al., 2019). In orthotics, powered orthoses have evolved from the heavy, rigid designs of the 1970s to lightweight exoskeletons like ReWalk, Ekso, Rex, and the Vanderbilt Exoskeleton, which use actuators and AI to assist mobility in patients with spinal cord injuries or neurological disorders (Awad et al., 2017). Functional electrical stimulation (FES) systems further complement orthotic advancements by stimulating muscles to facilitate movement, particularly in rehabilitation settings (Gorgey et al., 2021). These innovations collectively enable amputees and individuals with disabilities to perceive their devices as natural extensions of their bodies, mitigating social stigma and supporting emotional healing.

3. Mechanisms of Robotics in Prosthetics and Orthotics

The integration of robotics into prosthetics and orthotics has significantly advanced assistive technology, enabling enhanced functionality, rehabilitation, and mobility for individuals with limb loss or neuromuscular impairments. Robotic systems, particularly exoskeletons and wearable robotics, are designed with sophisticated mechanisms that address diverse needs, from therapeutic motor re - learning to human performance augmentation. These mechanisms leverage advanced sensors, actuators, and control systems to facilitate natural movement, compensate for disabilities, and support rehabilitation without the constraints of energy consumption or portability in certain applications. Below is a detailed exploration of the mechanisms underlying robotic exoskeletons and wearable robotics, including their specific purposes and innovative applications, such as soft robotic devices for foot rehabilitation.

Robotic lower limb orthoses and exoskeletons are engineered with three primary purposes: human performance augmentation for healthy individuals, mobile assistive technology for those with disabilities, and therapeutic motor re - learning for neurologically impaired patients in clinical settings (Dollar & Herr, 2008). Unlike portable prosthetics, many robotic orthoses used for rehabilitation do not face energy consumption challenges, as computer processors, energy supplies, and actuators can be externally located rather than mounted on the device or user. This design facilitates motor learning by encouraging proper gait dynamics without the need for long - term functional replacement. For example, exoskeletons like ReWalk, Ekso, Rex, and the Vanderbilt Exoskeleton enable individuals with paraplegia due to spinal cord injury (SCI) to stand and walk, while also compensating for mobility - limiting conditions such as stroke, muscular dystrophy (MD), multiple sclerosis (MS), cerebral palsy (CP), traumatic brain injury, and spina bifida (SB) (Awad et al., 2017). These systems enhance user strength, provide superhuman capabilities, and support rehabilitation by guiding limbs along defined trajectories using on - board sensors to collect signals and actuators to transfer adaptable power, controlled by sophisticated algorithms (Esquenazi et al., 2012).

Wearable robotics, defined as anthropomorphic mechatronic systems that align with the human body's geometry, operate in harmony with the user's movements. These systems collect biomechanical signals from the limbs via sensors and deliver controlled power through actuators to execute precise movements along predefined trajectories (Pons, 2008). A notable application is in soft robotic devices designed for foot rehabilitation, particularly for conditions like drop foot associated with cerebral palsy, amyotrophic lateral sclerosis, multiple sclerosis, or stroke. One such prototype, developed using soft materials and pneumatic artificial muscles (PAMs), mimics the muscles, tendons, and ligaments of the lower leg. Equipped with lightweight sensors and advanced control software, this active orthotic device achieves natural ankle motion, generating a sagittal range of motion of 27 degrees—sufficient for a normal walking gait (Wehner et al., 2013). Four PAMs, corresponding to three foreleg muscles and one posterior muscle, are connected to artificial tendons, enabling precise control of ankle movement. This mechanism supports rehabilitation by facilitating natural gait dynamics, reducing the physical and emotional burden of neuromuscular disorders.

These advancements highlight the versatility of robotic mechanisms in prosthetics and orthotics, from rigid exoskeletons that restore mobility to soft wearable systems that aid rehabilitation. By leveraging external power sources and advanced control systems, these devices prioritize therapeutic outcomes and user comfort, aligning with the goal of integrating assistive technology seamlessly into the user's body and lifestyle.

4. Why Amputees Need Powered Prostheses

Powered prostheses represent a transformative advancement in assistive technology, addressing a critical limitation in traditional prosthetics by providing the ability to generate energy, or "power, " which is essential for replicating natural human walking. Natural walking comprises four key elements: stability to walk, absorption of shock with each step, storage and release of energy for the next step, and the generation of active power to propel the body forward. Historically, prosthetic devices have effectively provided the first three elements—stability, shock absorption, and energy storage—through passive mechanisms like springs and dampers. However, the fourth element, the ability to create energy akin to the action of biological muscles, has been absent in traditional designs, limiting their functionality and efficiency (Herr & Grabowski, 2012). Powered prostheses, such as Össur's Power Knee and iWalk's PowerFoot BiOM, address this gap by incorporating robotic systems with actuators and microprocessors to deliver active power, mimicking the roles of the foot, calf, and knee muscles. These devices drive new energy into each step, enabling more natural gait patterns, reducing energy expenditure, and improving mobility for amputees, particularly in demanding tasks like climbing stairs or navigating uneven terrain (Au et al., 2008).

Robotic limbs have further advanced the capabilities of powered prostheses by integrating sophisticated control systems and neural interfaces. For instance, the Boston Digital Arm offers movement across five axes, providing enhanced dexterity for upper - limb amputees. Similarly, the i - Limb hand by Touch Bionics features five individually powered digits and a manually rotatable thumb, allowing precise and versatile hand movements (Belter et al., 2013). The RSL Steeper BeBionic hand exemplifies how robotic prosthetics combine lightweight materials with advanced actuators for improved functionality. Recent advancements also include brain - computer interfaces that translate neural signals into prosthetic motion, enabling intuitive control, as seen in systems like the Modular Prosthetic Limb (Collinger et al., 2013). In lower - limb prosthetics, devices like the iWalk PowerFoot BiOM use robotics to replace the missing calf muscle and Achilles tendon, offering active push - off during stair climbing or walking. Similarly, the Genium X2 knee employs a complex system of gyroscopes, accelerometers, and microprocessors to anticipate and adjust hydraulic cylinders for flexible, movable, or rigid configurations based on the user's activity, ensuring seamless transitions across diverse movements (Hafner et al., 2017). By providing active power and intelligent control, powered prostheses not only restore functional mobility but also reduce physical strain and enhance emotional well - being by enabling amputees to engage more fully in daily activities, aligning the prosthetic with the natural biomechanics of the human body.

5. Results

The integration of robotics into prosthetics and orthotics has significantly advanced assistive technology, offering enhanced functionality, mobility, and emotional well - being for individuals with limb loss or neuromuscular impairments. Powered prostheses, such as Össur's Power Knee and iWalk's PowerFoot BiOM, deliver active power to mimic the biomechanical role of muscles, enabling natural gait patterns and reducing energy expenditure during activities like stair climbing or walking on uneven terrain (Au et al., 2008). Myoelectric prosthetics, like the i - Limb and Boston Digital Arm, utilize electromyography (EMG) signals and machine learning to provide precise, intuitive control of multi - articulated limbs (Hargrove et al., 2017). Microprocessor - controlled devices, such as Ottobock's C - Leg 4 and Genium X2, employ sensors and adaptive algorithms to ensure stability and adaptability across diverse environments (Sawers & Hafner, 2016). Targeted muscle reinnervation (TMR) enhances prosthetic control and reduces phantom limb pain by rerouting nerves to alternative muscle sites (Dumanian et al., 2019). In orthotics, robotic exoskeletons like ReWalk, Ekso, and the Vanderbilt Exoskeleton enable mobility for individuals with spinal cord injuries (SCI) and support rehabilitation for conditions such as stroke, muscular dystrophy, and cerebral palsy (Gorgey et al., 2021). Soft robotic orthoses, using pneumatic artificial muscles (PAMs), achieve natural ankle motion for rehabilitation of drop foot, generating a sagittal range of motion sufficient for normal walking (Wehner et al., 2013). These advancements have restored functional independence, reduced physical strain, and mitigated social stigma, aligning with the goal of integrating assistive devices as natural extensions of the body.

6. Discussion

Robotic prosthetics and orthotics have transformed the landscape of assistive technology by addressing critical limitations of traditional devices, particularly the lack of active power generation essential for natural human movement (Herr & Grabowski, 2012). Powered prostheses, such as the PowerFoot BiOM, replicate the function of biological muscles, improving gait efficiency and user confidence in complex tasks. Myoelectric systems and neural interfaces, like those in the Modular Prosthetic Limb, enable intuitive control through brain or nerve signals, though challenges such as the invasiveness of neural implants and high costs persist (Collinger et al., 2013). Robotic exoskeletons, including ReWalk and Ekso, serve multiple purposes—augmenting performance for healthy individuals, assisting mobility for those with disabilities, and facilitating motor re - learning in clinical settings (Awad et al., 2017). Soft robotic orthoses, leveraging lightweight materials and PAMs, offer promising solutions for rehabilitation, particularly for neuromuscular disorders, by providing adaptable, natural motion without the energy consumption constraints of portable devices (Wehner et al., 2013). However, limitations such as battery life, device weight, and accessibility due to cost remain significant barriers. Future research should prioritize developing cost - effective, energy - efficient systems and non - invasive neural interfaces to enhance adoption. Additionally, integrating sensory feedback to restore tactile sensation could further improve user experience and emotional connection to the device. By addressing both physical and psychological needs, robotic prosthetics and orthotics reduce social stigma and foster reintegration, aligning with the vision of seamless human - device integration (Hussain et al., 2021).

7. Conclusion

The application of robotics in prosthetics and orthotics has ushered in a new era of assistive technology, providing amputees and individuals with mobility impairments with advanced, intuitive, and functional solutions. Technologies such as powered prostheses, myoelectric systems, microprocessor - controlled joints, and robotic exoskeletons have overcome the limitations of traditional devices by delivering active power, precise control, and adaptive functionality. Soft robotic orthoses and neural interfaces further expand the potential for rehabilitation and mobility restoration, particularly for neurological conditions. Despite challenges like cost, battery life, and accessibility, these advancements align with the Artificial Limb Program’s 1945 vision of enhancing quality of life by enabling users to perceive their devices as natural extensions of their bodies (Robot Institute of America, 1980). Continued innovation in lightweight materials, energy efficiency, and sensory integration will be critical to making these technologies more inclusive, ensuring that robotic prosthetics and orthotics meet the diverse needs of users worldwide while supporting both physical and emotional well - being

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