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Engineering Neural Prosthetics for Restoring Function

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ABSTRACT

Neural prosthetics represent a groundbreaking intersection of neurobiology, biomedical engineering, and artificial intelligence, offering hope for individuals with neurological impairments. These devices facilitate the restoration or augmentation of lost sensory and motor functions through neural interfaces. The evolution of neuroprosthetics has led to sophisticated systems that decode brain signals, enabling precise control of external devices such as robotic limbs and exoskeletons. This paper examines the fundamental neuroscience principles behind neural prosthetics, the various types of invasive and non-invasive prostheses, and the critical design considerations, including biocompatibility and sensory feedback mechanisms. Clinical applications highlight their potential in treating movement disorders, paralysis, and sensory deficits. Despite advancements, challenges such as long-term biocompatibility, ethical concerns, and neural adaptation remain. The integration of machine learning and advanced biomaterials promises further refinements, pushing the boundaries of neuroengineering and paving the way for highly intuitive, patient-specific prosthetic solutions.

Keywords: Neural prosthetics, neuroengineering, brain-computer interface (BCI), invasive prosthetics, non-invasive prosthetics.

INTRODUCTION

Neuroprosthetics devices are crucial in rehabilitation, combining advancements in neurobiology, bio-signal processing, electronics, and neural prostheses. Their appeal lies in restoring functions for disabled individuals and uncovering nervous system principles. Neuroprosthetic design is tailored to the type and location of neurological disabilities and intended outcomes. Market demand has led to a surge in multifunctional and multichannel neural prostheses. Electromagnetic brain signals can now be captured via multiple electrodes, either implanted or surface-mounted, allowing real-time analysis and control of neuroprosthetic devices. Enhanced understanding of brain activities at cellular, synaptic, and systemic levels may foster novel neurological treatments. Neuroengineering merges engineering with neurobiology, emphasizing tools and applications in rehabilitation and neurological function. There is a burgeoning interest in therapies for neural impairments by integrating neuroscience and engineering. Neuroprosthetics focuses on developing biomedical devices that replace or augment lost neural functions to enhance individuals' quality of life. The collaboration between engineering and neuroscience informs the organization of neuroprosthetic devices based on the brain's physiological characteristics. Techniques for recording invasive signals from implanted microelectrodes have been tested to control external robotic arms or paralyzed muscles, with unique brain signal features translated into control signals for these external devices [1, 2].

Overview of Neural Prosthetics

A neural prosthetic replicates or enhances nervous system functions through interfacing technology, enabling control of devices by thoughts. They aim to restore lost sensations or movement capabilities. The evolution and prospects of neural prosthetics highlight diverse designs that interact with patients' nervous systems for sensory or stimulation purposes. Many devices have primarily been created for research purposes, particularly in studying animal brain functions. With rapid advancements in neurotechnology, these devices are being developed for patients with neurological or psychiatric disorders. Currently, electrical stimulation and drugs are common interventions to manage disorders, making neural prosthetics a promising alternative. Such devices can gather brain data, potentially leading to enhanced performance and new insights into neural function. The overview of neural prosthetics encompasses their goals, history, categories, and technology. Future developments in neural prosthetics are expected to significantly advance neural engineering and neurorobotics. However, the development poses challenges, requiring the integration of diverse fields like neuroscience and robotics. Ensuring safety is paramount since the technology is implanted in humans, yet no established standards exist for implantable devices regarding safety assurance [3, 4].

Neuroscience Fundamentals

At the foundation of neuroscience are the basic principles that drive the understanding of how the human body functions, how reflexes work, and how signals are transported through the body. The human nervous system, comprising the central nervous system (CNS) and peripheral nervous system (PNS), exhibits an elaborate structure allowing for an extensive number of neural pathways. These pathways are vital in grounding the communication of signals between body parts and initiating proper motor responses. The body moves and feels sensations through the operation of triggers and responses binding in both the CNS and PNS. The biological medium for the implementation of these triggers and responses is within the neurons, synapses, and their action by way of neurotransmitters. The sensation is picked up at sensory receptors by the PNS and sent on to the CNS to be translated. In the same vein, motor inputs are received from the CNS by the PNS and then are acted upon by the body. The brain contains a wealth of different pathways and circuitry, meaning that it is the result of the operation of many regions working in parallel across the whole of the cerebrum. Different brain regions and spinal tracts correspond to different motor and sensory functions, highlighting the interactions required when designing targeted prosthetics. An understanding of basic neuroscience principles informs the approach to developing neuroprosthetics. Prosthetics may be made to mimic the physiological responses of the body, such as different types of signaling or the response to varying stimuli. Understanding the science behind different reflex arcs can make it easier to exploit neural pathways when programming a prosthetic. On a broader level, different types of functionalities can come from careful manipulation of neural circuitry when implementing a prosthetic device. With a grip of the underpinning in spur to neuroscience, these technicalities are surer to embody in the minds of those seeking a career with an approach to a neuroprosthetics firm, during both the design and implementation of prosthetic technologies [5, 6].

Neural Anatomy and Physiology

To design effective neural prosthetics that restore movement, understanding the nervous system's anatomy and physiology is crucial. This paper reviews the microstructure, including the brain, spinal cord, and neuronal networks for movement and sensory processing. Neural prosthetics must connect with the nervous system, highlighting the importance of its circuits for effective interfacing. The central nervous system (CNS) oversees complex tasks, while peripheral systems facilitate movement through spinal cord and muscle feedback. The cortex, mainly involved in voluntary movement, contains areas that control the body's functions, including fingers. Prosthetic arms usually link to the motor cortex through invasive micro-electrode arrays. The cerebellum refines commands from the cortex for fast, involuntary actions. The spinal cord is essential for handling muscle contractions and autonomic processes, transmitting sensory information back to the brain; for instance, withdrawal reflexes from painful stimuli bypass conscious processing. The spinal cord, divided into cervical, thoracic, lumbar, and sacral regions, organizes motor pathways into upper and lower neurons for movement execution. The CNS processes signals while the PNS aids command execution and provides feedback. Prosthetic arms can decode movement signals from neural implants and supply sensory information to the CNS. Regardless of challenges from neuron damage, effective integration with biotic systems is possible. Understanding nervous system anatomy and physiology is vital, as the brain processes information while the spinal cord and PNS manage movements. This system holds commercial potential for prosthetics and exoskeletons. Research indicates that neural prosthetics can influence changes in the primary somatosensory and motor cortices. The CNS coordinates complex actions like reaching for an object, requiring precise muscle contractions and feedback. The brain's cortex, crucial for voluntary motions, governs the entire body, including dexterous finger control. Commercial prosthetic arms often connect with the motor cortex through surgical procedures involving micro-electrode implants. The cerebellum enhances fast, automated movements based on experience and feedback. The supplementary motor area (SMA) plays a role in initiating movement but is less active during habitual tasks. The spinal cord transmits movements into action by sending signals and sensory feedback to the brain. For instance, spinal nerves relay pain signals to muscles, allowing for immediate reactions without cognitive awareness. Overall, the spinal cord's organization into regions allows for efficient control of motor functions, including finger control, leading to enhanced usability in advanced prosthetic applications [7,8].

Types of Neural Prosthetics

Neural prosthetics is an exciting field of biomedical engineering that focuses on developing artificial devices that facilitate humans to restore lost body functionalities that result from neurological conditions. There are two primary categories of neural prosthetics – invasive and non-invasive prosthetics. Invasive neural prosthetics need to be surgically implanted in the human body. As these devices have direct contact with neural tissues, they may result in more effective methodologies resulting in highly controlled action from the device. However, these devices may not be safe for long-term implantation due to the potential risk of infection and tissue damage. A non-invasive neural prosthetic does not need surgery and is placed in an external region of the human body. For example, surface electrodes are placed on the skin, or a wearable system, for example, a helmet. Non-invasive devices do not directly connect with neural tissues. Although they have lower effectiveness due to poor control and limited access to desired neural stimulants, they are more comfortable for users and safe. For example, a common application of non-invasive devices is placed over the head. Some alternatives are on the invasive side and do not surgically require implantation. They could potentially involve risk and comfort issues as well. However, this part focuses on the traditional classification of two broad categories for practicality. As this is a very diverse area, neural prosthetics can further be classified into various types based on their specific application and methodology. Examples of further classification can be as follows: stationary or transportable, used for restorative or supplementary tasks, based on their performance, etc. The fixed categories have been elaborated here with their advantages, limitations, and case study example applications. For a full appreciation of the diverse landscape of neural prosthetics, the chosen type of neural prosthetic should be critically assessed to reveal its relevance to the specific neurological condition being addressed [9, 10].

Invasive Vs. Non-Invasive Prosthetics

Neural prosthetics, or neuroprosthetics, consist of complex components divided into two categories: surgically implanted and externally worn devices. They can be invasive, penetrating the skin, or non-invasive, making contact with the body's surface. This dissertation primarily examines bioelectrical signals like electrochemical impulses, comparing the nervous system's bioelectrical signals with other internal phenomena, particularly electromyographic waves from muscles. Commercial neuroprosthetics vary widely in function. External devices can either touch the user or remain separate, including metabolic and imaging techniques. Sensory neuroprosthetics, mostly external, connect with mechanoreceptive nerve endings or photo-receptive neurons. Some naturally occurring devices, like the palplabrum, and many piezoelectric implementations translate mechanical forces into electrical signals. Mechanical receptors are categorized into three types: nervous system extensions, free nerve endings, and those responding to pressure, vibration, or displacement, influencing somatic sensations and pain perception. Their low-frequency mechanoception requires detecting tiny voltage changes from mechanical stimuli. In contrast, electrochemical spikes from nerves in muscle transmit impulses rapidly every 60-100ms, while capacitated nerve bundles create localized fields with high spatial accuracy. Although both intended signals and cortical components are identified on the scalp, peripheral nervous system connections are significantly faster, indicating robotic limits compared to natural high-degree-of-freedom control. Cochlear implants and certain visual prosthetics are two examples of devices that utilize signals from the neuromuscular system for functional outputs. The discussion extends to systems that stimulate the CNS through non-physiological inputs or outputs, focusing on EEG feedback therapies [11, 12].

Design and Development Considerations

Neural prostheses represent the interface between the brain or spinal cord and the limb, external device, or computer, thus enabling these to "communicate", to restore function in individuals with neurological disorders or injuries. The aim of both has been to create an interface between the nervous system and an external device to restore sensory perception or control movements. Extensive work is being done to develop highly efficient and reliable neural prostheses. Four wires were placed in the median nerves of amputees eliciting up to nineteen different degrees of freedom of finger movements. Multiple degrees of freedom with target-specific feedback for easy prosthesis control by amputees are challenging tasks. The goal is an intuitive and independent control of each finger of a dexterous prosthetic hand. One approach is to provide surgically reinnervated muscles access to the missing nerve signals related to complex movements. Another approach for restoring motor function in high-level spinal cord injuries is to extract the central nervous system signals that still encode movements either invasively or non-invasively. In either case, the signals are further processed with the use of advanced artificial intelligence techniques. Subsequently, these signals are used to control a robotized orthotic exoskeleton, which has enough degrees of freedom to mimic as closely as possible the real arm. Such an exoskeleton also provides the patient with neurological feedback related to various artificial sensors giving him/her the sense of the embodiment of the metal-based "new limb". To add to the dexterity of such orthotics, a gaming scenario has been implemented [13, 14].

Biocompatibility and Longevity

Biocompatibility and Longevity are essential in developing neural prosthetic systems. Biocompatibility involves materials safely interacting with biological tissues, avoiding harmful local or systemic reactions. Advanced materials processing aims to modulate the foreign body response to restorative implants due to aging, injury, or disease, but the extent to which changes at the biotic-abiotic interface led to predictable outcomes remains largely uncharacterized. This uncertainty poses challenges in creating effective, long-lasting implantable neural prostheses. Current biomaterials must perform well in biological environments, particularly in neuro interfaces, where charge delivery is critical and significantly impacts the surrounding tissue's geometry, chemistry, and reactivity. The fields of advanced materials and microsystems technology are expected to enhance materials beyond merely addressing biocompatibility concerns, actively seeking solutions to known challenges. The biocompatibility of implanted devices is closely tied to patient outcomes, as adverse reactions can hinder device effectiveness and lead to removal. This is particularly critical in neural interface technology, which carries risks of neural tissue loss and glial scarring that can disrupt device-tissue connections. Ensuring a stable and viable neural interface throughout a patient's life presents profound challenges. Longitudinal studies in animal models are increasingly employed to investigate the longevity of neural technologies and to understand how device-tissue interactions evolve. Such research is vital for designing devices, materials, and surgical protocols that enhance long-term performance and reduce risks. Therefore, advancing biocompatible materials that integrate maximally with living tissue over extended periods is crucial [15, 16].

Sensory and Motor Interfaces

At the heart of neural prosthetics for sensory restoration, sensory feedback is enabled by the information transfer from the artificial skin sensors to the non-intact sensory nerves or the residual neural system. This design uses the residual neural system after amputation and complements it with bioengineered skin sensors. The sensors provide a soft and biocompatible interface with the surrounding tissue and electrically stimulate the peripheral nerve through implanted electrodes. The rational and rapid decisions during grasping are made possible by the feedback derived through efferent and afferent pathways. This advanced prosthetic system enhances the user experience and provides an effectual strategy that is essential for the completion of a targeted task. A prosthetic arm user is required to pick up objects of different shapes and properties, and delicate objects could break when grasped with excessive force. The application receives information about the object to be grasped from the view of an RGB-D camera, while the applied commanded force by the user to move the hand is recorded by the sensory feedback system. Feedback from implanted neural electrodes allows the user to feel the object being grasped by artificial mechanoreceptors and adjust the commanded force according to the object's fragility. In more than 90% of the grasping events tested, optimal forces were applied that were safe enough to avoid breaking the object. These results reveal for the first time that naturalistic grasping can be achieved with bioengineered sensory feedback, with immediate findings in prosthetic rehabilitation [17, 18].

Sensory Feedback Mechanisms

Neural prosthetics have the potential to replicate lost limb functions, but progress is hindered by the crucial role of sensory feedback in the motor system. Sensory information is vital for controlling movement, and offering real-time updates about interactions with the environment. This feedback loop refines motor control and influences psychological aspects like ownership and agency over one's body. Research shows that effective motor prosthetics depend on sensory feedback; without a complete feedback system, individuals with limb loss face challenges in mechanical performance and functional restoration.

Properly modulated grip and coordinated movements demand proportional feedback. Current systems rely heavily on visual feedback, which increases cognitive load and limits grasping effectiveness. In contrast, sensory feedback enhances object manipulation, allowing stable grips even with less visual attention. Tactile and proprioceptive feedback modes require less cognitive effort compared to visual cues. There are ongoing inquiries about muscle-tendon changes during phantom or residual limb contractions with prosthetic hands, crucial for fostering familiar sensations during grasping. Natural sensory feedback improves ownership, embodiment, and motor control; it is well integrated into the body's sensorimotor learning systems. Combining various feedback modalities—tendons, muscles, skin, and vision—may enhance effectiveness. Integrating feedback loops into prostheses could lead to more natural and intuitive device control, fostering advanced systems that support user learning and adaptation to new prosthetics [19, 20].

Clinical Applications

For decades, engineering neural prosthetics has been limited to academia, with experiments conducted on animals to eventually aid humans. Recent technological advancements have improved the development and accessibility of neural prosthetics, leading to their application in various clinical settings. Case studies show how neural prosthetics can treat movement disorders, such as restoring motor function in paralyzed patients, aiding limb amputees, and alleviating symptoms in those with chronic pain, epilepsy, or Parkinson's disease. Personal stories of movement disorder experiences are intertwined with technical insights on the use of neural prosthetics. A notable study featured a 24-year-old quadriplegic female with a neurally controlled FES-BCI system, exploring recording zones in her spinal cord. Collaborative lab efforts enabled light touch control via a BCI, allowing a robotic gripper to function. The text discusses challenges and new questions arising from this research, along with the unsatisfactory outcomes of current implementations. It highlights the limitations of existing technology and the need for personalized approaches. In recent years, neural prosthetics have sparked hope for those with previously incurable disabilities. Among movement disorders, paralysis is particularly debilitating, affecting limb control and autonomic functions. Although devices like Vagus Nerve Stimulation can aid bowel and bladder control, restoring limb movement remains complex. While technology holds great potential, engineering challenges and ethical concerns hinder substantial progress, leaving many neural prosthetic solutions still theoretical and inconsistent in results [21, 22].

Neural Prosthetics in Movement Disorders

Movement disorders are a highly prevalent group of neurological diseases among or even more aligned patients, comprising primarily Parkinson's disease (PD), and essential tremor (ET). These diseases are characterized by developing detrimental effects on basic functions performed in everyday life, through deteriorating properties like bradykinesia, rigidity, and tremor. If conventional treatments are not fully effective, neural prosthetics are shown to be highly effective in the improvement of life quality. These neuromodulatory treatment approaches interact with the neural circuits responsible for controlling the physiological movements of the body. As such, effects in the restoration of muscle functionalities, speaking the right sequence of words in the correct order, stance stability, or ameliorating bradykinesia and dyskinesia, are subsidiary after the treatment of movement disorders. Through the aforementioned mechanism, the patient gains the ability to aesthetically improve the usability of his/her impaired mobility, to incorporate the appliance of the device into the affected daily activities, and through the clinical instrumental assessment in shaping the neuromodulation device more precisely through the trigger thresholds or programs. This is important to use the extensive parameters of the device more effectively for boosting the optimal neuromodulation of local neural circuits. Real patient case studies are presented, each highly articulated to effectuate enhancements in the important attributes of the life quality. Importantly, the customization of the device settings is analyzed through the extracted clinical therapeutic effect maps in long clinic settings. Due to the variability of the patient's physiological condition, effective neuromodulation is brought only with the proper subject-specific tailoring of the device settings. Some of the critical issues that are faced in the long-term effectual deployment of neural prosthetics are discussed, with partial solutions to ease these difficulties. Neuroprosthetic research for treating movement disorders is elaborated, especially for the unconditionally adjustable neuromodulation, proper feedback that is crucial concerning the therapeutic effect adaptation [23, 24].

Challenges and Future Directions

The development of implantable devices for interfacing with the nervous system, so-called neural prosthetics, has improved the life quality of many persons suffering from loss of limb mobility or sensory functions. Applications of neural prosthetics include artificial limbs, stand-alone devices that are controlled by brain signals, or cortical and retinal stimulation devices that are aimed at replacing damaged or lost sensory input. Furthermore, opportunities are being explored for neural prosthetics to be connected to the neocortex or other parts of the brain and between different persons. In this frontier work the use of bidirectional interfaces is planned and therefore an electrical joint will be established that permits the bidirectional transfer of neuronal signals between the artificial device and the host nervous system. This review will begin by presenting illustrative examples of the state-of-the-art development and applications of neural prosthetics based on unidirectional interfacing technology. Refinements on future applications and experimental schemes that will require bidirectional interfaces are then discussed including brain-computer interfaces to control more complex, shared, or cooperative systems; or systems that act induced by voluntary and evoked activity in the CNS; sensory neuroprosthetic devices to close the sensory-motor loop in tetraplegic patients or, in robotics research, the use of cortical signals to provide artificial sensory inputs to control movement. Finally, the focus will be on recent progress in research apt to provide bidirectional interfaces as well as work-in-progress attempts to extend the control of an anthropomorphic robot arm to several degrees of freedom using intracortical recordings as sources [25, 26].

Ethical and Societal Implications

Human life has been transformed through tools and technologies that replace or enhance capabilities. Canes, crutches, hearing aids, pacemakers, and communication devices serve as instruments that modify or repair bodily functions. Prosthetic devices can augment the body, enabling capabilities not otherwise possible. For conditions like Parkinson's, subthalamic nucleus (STN) ablation is a potential treatment; however, precision is critical as misplaced lesions can cause cognitive issues. Closed-loop deep brain stimulation (DBS) can modulate neural activity, with the STN being a common DBS target. Given the small size of the STN and its deep location, the safety of procedures is vital. Most implants lack neural activity recording capabilities. High costs associated with database algorithms and neurologist involvement may render DBS treatments unfeasible. Ongoing interdisciplinary research aims to overcome these challenges through neural prosthetics. Direct sensing of neural signals has the potential to enhance treatments to restore lost functions. Technologies measuring brain activity—via electric potentials, magnetic fields, or blood flow—have emerged in neuroscience and neuro-engineering. Recently, depth-invasive methods with high resolution have gained attention for investigating neural mechanisms, particularly in areas like angular gyrus (AG) and BA44 for anthropological reconstruction. They also support brain-computer interfaces (BCI) that enable control over external devices, such as speech synthesizers and neuroprosthetics. Machine learning has been effectively used to distinguish neural signals tied to various mental states. Hyper-direct stimulation of the prefrontal area can disrupt behavior when engaging with the right inferior parietal lobe and AG [27, 28].

CONCLUSION

The development of neural prosthetics has revolutionized rehabilitation for individuals with neurological disorders, bridging the gap between biological neural networks and artificial systems. Advances in bioelectronics, neurobiology, and artificial intelligence continue to refine these devices, improving precision, usability, and integration with the human nervous system. While challenges such as biocompatibility, safety, and ethical considerations persist, ongoing research in material science, signal processing, and neuroplasticity adaptation is paving the way for more effective and long-lasting solutions. Future innovations will likely emphasize personalization, adaptability, and enhanced sensory feedback to ensure seamless human-prosthetic interaction. Ultimately, neural prosthetics hold immense promise in restoring autonomy and improving the quality of life for those affected by neurological impairments.

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