

The Application and Development of Brain-Computer Interface in the Treatment of Neurodegenerative Diseases

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Abstract: Neurodegenerative diseases such as Alzheimer's disease (AD), Parkinson's disease (PD), and amyotrophic lateral sclerosis (ALS) cause progressive loss of cognitive, motor, and communication functions, often resulting in severe disability. Traditional treatments mainly alleviate symptoms but rarely halt disease progression or restore function. This review examines the therapeutic potential of brain-computer interface (BCI) technologies across three domains: cognitive recovery, motor rehabilitation, and communication enhancement. Advances in BCI-based cognitive training have shown improvements in executive function and memory, while motor imagery (MI)-based BCIs combined with neuromodulation or functional electrical stimulation have enhanced motor outcomes in stroke and PD. Invasive and non-invasive BCIs have also enabled communication in patients with severe motor impairments. Hybrid EEG-fNIRS systems and integration with artificial intelligence and natural language processing further improve decoding accuracy and user experience. BCIs offer a promising, non-pharmacological, and patient-centered solution that complements existing therapies and may significantly enhance autonomy and quality of life for individuals with neurodegenerative conditions.

Keywords: Neurodegenerative diseases, Brain-computer interface, Alzheimer's disease, Parkinson's disease, amyotrophic lateral sclerosis

1. Introduction

Neurodegenerative diseases, such as AD, PD, and ALS, are characterized by progressive and irreversible loss of neuronal structure and function. These disorders often lead to severe impairments in memory, cognition, motor control, and communication, significantly diminishing patients' quality of life. Globally, the burden of neurodegenerative diseases is rising at an alarming rate. According to the World Health Organization, over 55 million people worldwide are currently living with dementia, and this number is expected to reach 139 million by 2050 [1]. PD, the second most common neurodegenerative disorder after AD, has also seen its prevalence increase significantly in recent years [2]. Given the aging global population, these numbers are projected to continue increasing, placing enormous pressure on healthcare systems and caregivers.

Despite years of research, the main treatments available for neurodegenerative diseases tend to focus on managing symptoms rather than stopping or reversing the underlying progression, and their effectiveness remains quite limited. Pharmacological approaches often target neurotransmitter

systems to alleviate symptoms, but fail to address the underlying neurodegeneration [3]. Non-pharmacological treatment methods, such as physical therapy and cognitive training, may improve functional outcomes to some extent. However, these interventions alone are often insufficient to achieve significant and sustained rehabilitation outcomes. Additionally, many existing treatment methods lack personalization and are constrained by side effects, inconsistent efficacy, and the heterogeneity of disease progression. These limitations highlight the urgent need for novel treatment strategies that not only alleviate symptoms but also enhance the brain's neuroplasticity and functional recovery capacity.

BCI technology is showing real potential as a valuable option in this area. BCIs are systems that enable direct communication between the brain and external devices by decoding neural signals, often acquired through electroencephalography (EEG), functional magnetic resonance imaging (fMRI), or electrocorticography (ECoG) [4]. By bypassing neuromuscular pathways, these interfaces allow users with severe motor or communication impairments to interact with external systems without relying on muscular activity. By circumventing impaired neuromuscular pathways, BCIs provide alternative communication and control channels for those otherwise unable to perform essential tasks. Beyond restoring communication and control, BCIs deliver real-time neurofeedback and facilitate neural plasticity, thereby enhancing both motor and cognitive rehabilitation [5].

BCIs present a versatile and promising tool in the treatment of neurodegenerative diseases by enabling real-time brain-based interaction without relying on intact motor pathways. Their ability to support user-specific neural adaptation allows them to align with the heterogeneous and progressive nature of disorders such as AD, PD, and ALS. Non-invasive and modular by design, BCIs can be integrated at various stages of disease progression and tailored to diverse clinical objectives—including cognitive rehabilitation, motor re-education, and communication support. For example, recent studies have shown that BCIs enhance cognitive training in patients with early-stage AD [6], improve motor function in individuals with PD when combined with functional electrical stimulation or neuromodulation [7], and restore basic communication in patients with advanced ALS or locked-in syndrome through both invasive and non-invasive systems [8,9].

Moreover, recent reviews of classification algorithms for EEG-based BCIs highlight that modern machine learning approaches—such as convolutional neural networks, common spatial pattern classifiers, and adaptive ensemble methods—have significantly enhanced decoding accuracy and system adaptability [10]. These AI-enhanced BCIs can recognize user-specific neural patterns and adjust to signal variability, offering more stable, efficient, and intuitive control. These technological advances signal a paradigm shift from experimental prototypes to clinically viable neurotechnologies capable of engaging the brain's intrinsic plasticity and facilitating functional recovery in neurodegenerative populations.

This review aims to explore the recent advances in the application and development of BCIs in the treatment of neurodegenerative diseases. The discussion focuses on three major domains: cognitive recovery, intervention in motor disorders, and enhancement of communication capabilities. This review explores the latest technological developments and clinical results related to BCI-based interventions, emphasizing both what's been achieved recently and the potential directions for future research in managing neurodegenerative conditions.

2. The application and development of BCI in the treatment of neurodegenerative diseases

As neurodegenerative diseases impair cognition, movement, and communication, BCIs offer new therapeutic possibilities beyond conventional treatments. The following sections examine how BCIs are being applied in these three domains, beginning with cognitive recovery.

2.1. BCI in cognitive recovery for neurodegenerative diseases

Cognitive impairment is a hallmark feature of neurodegenerative diseases such as AD, frontotemporal dementia (FTD), and Lewy body dementia (LBD), each with distinct neural degeneration patterns. AD typically involves hippocampal and temporoparietal atrophy resulting in episodic memory loss, FTD affects frontal regions crucial for planning and inhibition, and LBD manifests with attention deficits and hallucinations. These impairments significantly reduce autonomy and quality of life and pose challenges for existing therapies, which offer limited specificity and rarely prevent disease progression. In contrast, BCI technologies have emerged as promising non-pharmacological tools, especially for early or prodromal stages such as mild cognitive impairment (MCI), offering personalized interventions that stimulate residual neuroplasticity and reinforce preserved networks.

BCI-based cognitive rehabilitation typically uses noninvasive EEG systems to translate real-time brain activity into neurofeedback or gamified training tasks. These paradigms reinforce task-related neural circuits through immediate performance-related feedback, thereby promoting synaptic potentiation and functional network reorganization. Jeunet et al. (2016) showed that tailored EEG-based BCI training improved attention regulation and cognitive flexibility in older adults [11, 12]. More recently, Nguyen et al. developed a gamified executive function training program that significantly improved motivation and goal-directed behavior in older participants [13]. Critically, these approaches can be customized to cognitive profiles and disease stage, supporting adaptive, patient-specific intervention plans.

In neurodegenerative-specific populations, clinical studies provide early evidence of efficacy. WilkośćDębczyńska et al. conducted a randomized controlled trial using theta/alpha neurofeedback in individuals with MCI and early dementia, reporting significant improvements in memory, language, and attention after training [6]. Similarly, the systematic review by Tazaki (2024) across studies of MCI and mild AD showed consistent enhancement in memory, attention, and executive function through neurofeedback interventions, regardless of protocol heterogeneity [14]. These real-world data underscore that BCI interventions are not merely proof-of-concept—rather, they demonstrate tangible benefits in neurodegenerative populations.

Hybrid BCI systems combining EEG with functional near-infrared spectroscopy (fNIRS) further enhance spatial precision and signal robustness, particularly relevant in detecting prefrontal activation under cognitive load [15]. In addition, case-level evidence supports feasibility in early-stage AD: McLaughlin et al. reported on a small pilot (five participants with mild AD) using an EEG-based neurofeedback system targeting reading and attention tasks. Participants learned to control the BCI and showed steady improvement in letter cancellation and processing speed measures over the intervention period [16]. These results offer proof-of-principle that BCI-guided cognitive training can be applied even in patients with mild AD. Mechanistic reviews also support the underlying rationale for BCI use. Vilou et al. summarized how EEG–neurofeedback interventions modulate theta, beta, and sensorimotor rhythm (SMR) patterns in dementia and MCI patients, effectively restoring disrupted network connectivity and enhancing cognitive domains impaired by disease [17]. Their review included multiple neurodegenerative cohorts and highlighted neuroplastic changes as measurable via EEG biomarkers, reinforcing that BCI training can produce lasting functional reorganization.

Nonetheless, challenges remain—interindividual variability, susceptibility to artifact interference, and the necessity for frequent calibration limit replicability across sessions. Moreover, many existing trials are brief and lack real-world generalization metrics, making it unclear whether training gains translate to daily functioning or delay progression. To address these gaps, future

studies should implement standardized neurofeedback protocols, extend follow-up duration, and embed multimodal interventions (e.g., combining with cognitive-behavioral therapy or remote monitoring).

In summary, BCI-based cognitive interventions show increasing promise in supporting cognitive resilience in neurodegenerative disease populations. By providing personalized, adaptive feedback grounded in neural activity, these systems can target domain-specific deficits—studies in AD and MCI patients confirm feasibility and preliminary efficacy. As neurodegenerative cognitive decline continues to challenge conventional treatment paradigms, BCIs offer a flexible, scalable approach aligned with precision rehabilitation and early clinical intervention.

2.2. BCI in motor rehabilitation for neurodegenerative disorders

Movement disorders, including PD, stroke-related motor impairment, and focal dystonia, severely compromise motor control, coordination, and independence in affected individuals. Traditional therapies offer limited functional recovery, particularly in chronic stages of disease. In recent years, BCI technology has gained attention for its ability to decode motor intentions from neural activity—typically using EEG—and convert them into control signals for assistive devices or neurofeedback. Meta-analytic evidence has shown that when BCIs are combined with functional electrical stimulation (FES), they can significantly improve upper limb motor function, particularly in post-stroke rehabilitation, suggesting promise for broader clinical use in neurodegenerative conditions [7].

One widely used approach involves MI-based BCIs, which require users to mentally simulate limb movement, thereby modulating sensorimotor rhythms detectable by EEG. These signals can then activate robotic actuators or trigger FES systems. Ren et al. demonstrated that combined BCI–FES training led to sustained improvements in motor outcomes, with effects persisting weeks after treatment completion [7]. Similarly, BCIs have been integrated with neuromodulatory techniques such as repetitive transcranial magnetic stimulation (rTMS) and neurofeedback. In a randomized controlled trial, Romero et al. (2024) showed that combining rTMS with EEG-based feedback in PD patients produced the greatest improvements in motor function and quality of life compared to either intervention alone [18].

To enhance signal decoding reliability, hybrid BCI systems that combine EEG with functional near-infrared spectroscopy (fNIRS) have been developed. These systems incorporate both electrophysiological and hemodynamic data, offering improved accuracy and stability. Chen et al. reported that EEG–fNIRS BCIs demonstrated superior classification performance and higher user engagement, particularly in complex or noisy environments [19]. This makes them particularly relevant for older adults and individuals with advanced disease, where single-modality systems may underperform. At the same time, more advanced techniques such as adaptive deep brain stimulation (aDBS) are being integrated into BCI frameworks. Unlike conventional DBS, aDBS dynamically adjusts stimulation parameters in response to real-time neural signals, improving motor control while minimizing side effects such as dyskinesia. Although still in early clinical stages, such feedback-driven neuromodulation systems represent a shift toward intelligent, closed-loop therapies [20]. Beyond stroke and PD, BCIs are being applied to a broader range of motor disorders. Simonyan et al. reported that MI-based BCIs helped alleviate symptoms in patients with task-specific focal dystonia, potentially through targeted motor reprogramming [21]. BCI-guided gait training has also shown preliminary effectiveness in improving balance and reducing fall risk in PD, though further validation in large-scale trials is needed [19].

Despite these advancements, barriers to widespread clinical adoption remain. EEG-based motor decoding is vulnerable to variability and noise, especially in patients with altered cortical dynamics. While hybrid systems improve accuracy, their technical complexity and higher cost may limit accessibility. BCI use also requires individualized calibration, which is time-consuming and resource-intensive. Furthermore, the heterogeneity of disease progression across individuals necessitates tailored treatment protocols, complicating standardization. Practical constraints—including device bulkiness, user training demands, and limited regulatory guidance—also hinder real-world deployment. Nevertheless, as Ren et al. emphasize, the future of BCI-based motor rehabilitation depends not only on technical refinements but also on interdisciplinary collaboration across clinicians, engineers, and healthcare systems [7]. Key priorities include developing adaptive algorithms capable of real-time calibration, establishing standardized clinical endpoints, and conducting large-scale, multi-center trials to validate clinical effectiveness across diverse neurodegenerative populations.

2.3. BCI for communication support in severe neurodegeneration

Communication barriers are profound and life-changing consequences of late-stage neurodegenerative diseases, particularly in patients with ALS, brainstem stroke, and other forms of motor neuron degeneration. As voluntary muscle control diminishes, patients may enter a locked-in state where cognitive abilities remain intact but expressive capabilities—especially speech—are entirely lost. Against this backdrop, BCIs have gradually become a viable and increasingly mature strategy for helping patients with severe motor disorders regain basic communication abilities.

In recent years, technological advances in the intracortical application of BCI systems have demonstrated the enormous potential for communication through direct decoding of neural activity. For instance, Willett et al. developed a high-performance intracortical speech neuroprosthesis that enabled a participant with severe paralysis to generate naturalistic speech at an average rate of 62 words per minute. By using deep learning models to decode high-resolution neural signals from the sensorimotor cortex, their system generated accurate sentence-level speech output with a word error rate of 23.8%, marking a breakthrough in restoring fluent and clear verbal communication through BCIs [8]. Similarly, Liu et al. (2023) demonstrated that intracortical BCIs can decode tonal language speech from neural activity and synthesize naturalistic spoken output with high accuracy using advanced deep learning algorithms [22], thereby extending the application of BCIs to multiple language environments. This improvement is particularly beneficial for patients who require fluent, context-aware communication support.

In addition to speech synthesis, speller-based BCI systems have been successfully employed in late-stage ALS and locked-in syndrome. These systems typically decode intended letter selections via neural activity patterns, often recorded through local field potentials or ECoG. Fan et al. introduced a self-calibrating intracortical BCI that enabled a user with tetraplegia to type reliably without recalibration over one year [9]. This signal stability and autonomy level marks a key advancement for BCI systems, moving toward plug-and-play functionality for real-world use.

Although fully invasive BCI systems offer high signal fidelity and precise control, their clinical application is limited by the complexity and risks associated with cranial surgery. To overcome these limitations, minimally invasive endovascular techniques have been developed as a promising alternative. One such innovative technology, the Stentrode device, enables chronic BCI functionality through transjugular implantation, eliminating the necessity of cranial surgery. Oxley et al. demonstrated that ALS patients using the Stentrode could independently perform practical digital tasks at home, such as email communication, online banking, and simple web browsing [23]. This

development shows how BCIs can be used in real-world, unsupervised settings, marking a key step forward for neuroprosthetic technology in clinical applications.

Non-invasive BCI systems remain essential for early-stage intervention and broader accessibility, particularly for patients unable or unwilling to undergo invasive procedures. Among these, auditory and visual spelling BCIs using EEG and event-related potentials have been extensively studied to help patients with complete locked-in syndrome achieve basic “yes/no” or letter-by-letter communication. Guger et al. demonstrated that a vibrotactile P300-based BCI system enabled command following and communication in locked-in and completely locked-in patients without requiring any muscular or ocular input [24]. Although non-invasive BCIs typically have slower information transmission rates than intracortical systems, they have reduced clinical risks and practical advantages regarding device setup flexibility and deployment in different clinical settings.

Multimodal and hybrid BCI systems have also become promising research directions for improving communication capabilities. By integrating EEG and fNIRS technologies, such systems can achieve more stable decoding performance, especially in complex clinical environments. For example, Qiu et al. developed a hybrid EEG-fNIRS interface based on multimodal feature fusion and incremental learning, significantly improving classification accuracy compared to single-modal systems, reaching up to approximately 96% [25]. This enhanced reliability in signal interpretation can translate into faster and more comfortable user experiences for communication purposes. In addition, current research is actively exploring the integration of BCI platforms with natural language processing technology and predictive text algorithms, which is expected to improve communication speed and enhance contextual fluency, especially for users with limited attention spans or cognitive fatigue [25].

Despite these advances, several challenges persist. Invasive systems require neurosurgical procedures, raising ethical and medical concerns for their routine use in vulnerable populations. Long-term reliability, signal degradation, and neuroplastic changes near implant sites can affect performance consistency [8]. Non-invasive systems, though safer, remain limited in throughput and are often sensitive to noise and user fatigue. In contrast, the cognitive effort required to use a spelling-based BCI may be considerable, especially for patients with severe neurodegenerative diseases [24]. Addressing these limitations will require innovations in hardware design, signal processing algorithms, and user-centered interface development.

Ethical considerations are equally critical in the implementation of BCI communication systems. Obtaining informed consent remains a significant challenge, particularly for individuals with impaired cognitive function or fluctuating decision-making abilities. Ensuring user autonomy requires continuous monitoring and reassessment of participants’ willingness and understanding. Additional concerns have been raised regarding the privacy of neural data and the potential misuse of sensitive brain information. Research emphasizes that without strong safeguards, BCI systems could threaten psychological privacy, promote “brainjacking” behavior, or lead to unauthorized access to users’ thoughts and intentions [26].

In summary, BCIs have made notable progress in restoring communication abilities in patients with neurodegenerative diseases. Invasive methods, including intracortical and intracerebral BCIs, have demonstrated high-resolution decoding capabilities suitable for speech synthesis and speed typing. At the same time, non-invasive and hybrid systems offer scalable alternatives with continuously improving reliability. As these technologies evolve, future efforts should prioritize minimally invasive solutions, long-term usability, personalized interfaces, and ethical safeguards to ensure equitable and meaningful access to communication for all affected individuals.

3. Barriers and future translation of BCI in neurodegenerative disease care

As BCI systems move from laboratory prototypes to real-world clinical tools, several unresolved challenges hinder their widespread application in neurodegenerative disease care. A major barrier is the lack of standardization across studies. Variability in signal modalities, training paradigms, trial durations, and outcome measures makes it difficult to compare results, replicate findings, or develop unified clinical protocols [7]. This inconsistency, combined with the predominance of small-sample trials, limits generalizability across diverse disease trajectories seen in AD, PD, and ALS [18].

Beyond methodological issues, practical integration into everyday care remains complex. Device portability, setup time, and patient fatigue are key factors, particularly for individuals with declining physical or cognitive capacity [19]. Additionally, while AI-enhanced decoding models have improved system performance, their complexity introduces challenges related to interpretability, algorithmic transparency, and clinical trustworthiness [10].

Ethical concerns further complicate long-term deployment. Patients with progressive cognitive decline may face difficulties in providing and sustaining informed consent [26]. As BCIs increasingly incorporate cloud-based processing and large language models, risks related to neural data privacy, mental autonomy, and unauthorized use of brain-derived information must be addressed [26].

To advance BCI technologies toward scalable and ethical implementation, future research should prioritize harmonized multi-center clinical trials, develop interpretable and adaptive AI models, and embed dynamic calibration mechanisms tailored to patient needs [9]. The long-term goal is to establish BCIs as components of multimodal, user-centered neurorehabilitation platforms—enhancing autonomy, cognitive resilience, and communication in individuals with neurodegenerative diseases [6, 8].

4. Conclusion

This review highlights the expanding role of BCI technology in the treatment of neurodegenerative diseases, focusing on cognitive recovery, motor rehabilitation, and communication support. Evidence increasingly supports BCI's potential to restore function and improve quality of life in patients with AD, PD, ALS, and related conditions. By enabling direct interaction between the brain and external devices, BCIs bypass damaged neuromuscular pathways and engage neuroplasticity mechanisms, offering novel therapeutic options where traditional interventions fall short.

In practice, BCI-based neurofeedback and gamified training platforms have shown benefits in enhancing executive function, attention, and memory among individuals with early cognitive decline. EEG and fNIRS systems provide real-time personalized feedback, facilitating cortical reorganization and patient engagement. In motor rehabilitation, BCIs paired with FES, robotics, or neuromodulation therapies such as rTMS have yielded significant motor gains and long-term functional improvements, particularly in stroke and PD populations. In communication, BCI technologies now enable patients with locked-in or complete locked-in syndrome to express themselves via EEG-based spellers, intracortical implants, and hybrid interfaces. With the integration of artificial intelligence and natural language processing, these systems have become increasingly accurate, intuitive, and adaptable.

The transition of BCIs from laboratory prototypes to real-world clinical applications marks a significant milestone. These systems are now being deployed in home and clinical settings, offering scalable, minimally invasive, and autonomous solutions. However, key challenges remain. Signal variability, calibration demands, and disease heterogeneity continue to impact performance and

reliability. Ethical concerns—particularly around informed consent, data privacy, and autonomy—must be carefully addressed, especially as BCI systems increasingly rely on AI and cloud-based infrastructures.

Future efforts should focus on improving decoding accuracy, reducing setup time, and enhancing multimodal integration (e.g., EEG–fNIRS–EMG). Clinically, there is a need for adaptive algorithms that accommodate individual neurological profiles and disease trajectories, supported by standardized outcome measures. Long-term, BCIs may evolve into wearable, AI-driven platforms offering closed-loop, real-time intervention, predictive diagnostics, and personalized rehabilitation. With interdisciplinary collaboration bridging neuroscience, engineering, and patient-centered care, BCI technologies are poised to become transformative tools in the management of neurodegenerative diseases—supporting autonomy, restoring communication, and promoting functional recovery across a range of clinical settings.

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