Proceedings of ICBioMed 2025 Symposium: Computational Modelling and Simulation for Biology and Medicine
DOI: 10.54254/2753-8818/2025.LD26246

Analysis of the Application Prospects of Brain-Computer Interface Technology in Medical Treatment and Recovery

Shangan Ge

Beijing No.4 High School International Campus, Beijing, China
shangan.ge@bhsfic.com

Abstract. The brain-computer interface (BCI) and its correlative techniques have been developed for decades since the BCI was brought forward and invented by Jacques J. Vidal as direct brain-computer communication, and this biological technique has been used in the current medical recovery and disability restoration in the medical system. Currently applied BCIs can precisely rebuild the connection that was broken in the disasters and caused the disability, especially in the nervous system. In this study, we reviewed the currently existing examples of the treatment with the participation of the BCI technique according to several different treatment requirements, including diagnosing and recovering from physical damage and neurological diseases. Additionally, we summarized the possible challenges and limitations of the BCI technique in the medical field. We gave an analysis and principles for developing the related biomedical application of BCI. According to the reviewed research and collected data in the study, BCI has an enormous prospect for medical applications and will change the conventional form of traditional treatment of neurological disability and physical damage to the nervous system. It is foreseeable that successful medical applications of BCI will experience a surge in the following decades. This study's results can be used to analyze the future development directions of the BCI technique.

Keywords: Brain-computer interface, Biomedical technology, Nervous system disorder, Medical treatment.

1. Introduction

In the current world and society, the incidence of acquired neurological diseases and physical disabilities related to injury or damage to the nervous system is increasing due to factors, including wars, drugs, and even simple accidents, such as emergent physical accidents, and so on. Patients can gradually lose their ability to control part of their body due to the damage, which is caused by the factors listed above, and even lose the injured organs completely [1]. Facing the increasing threat of nervous system disorders, the BCI can be a specific and effective solution for nervous system diseases and disabilities.

In recent decades, the BCI, a biomedical technique, has gradually entered the public's view. Since Jacques J. Vidal once invented it, scientists and doctors have increasingly found its application prospects in medical use, especially in restoring damage that affects the human nervous system. Vitro medical equipment can effectively substitute the damage-influencing functions and help

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DOI: 10.54254/2753-8818/2025.LD26246

patients with the relevant actions. The BCI can even be used to replace the function of the degenerated neurons to a certain extent, helping the patients with stimulation and nerve signal conduction. In a study of Amyotrophic lateral sclerosis (ALS), by applying a specific type of communication brain–computer interface, known as a speech neuroprosthesis, on two ALS patients and found that the neuroprosthetis is available and effective on speech function's restoring, Card et al. and Vansteensel et al. provide compelling new evidence of rapid progress in clinically viable, practical applications of brain–computer interfaces to restore communication to persons living with paralysis [2]. Promptly controlling the artificial prosthetic limbs, restoring the ability of sense, and incisively sensing the environment, as a high-precision technique, BCI has a wide range of application prospects in the medical field.

In this research, based on the currently existing studies and clinical experiments about the medical use of the BCI, we will summarize the possible future developing directions, and give advice and precepts for developing the relative technique's application.

2. Current BCIs for medical care – from therapy to recovery

2.1. BCI's fundamental information

Brain-computer interfaces help patients control medical devices using only their thoughts. These systems detect electrical signals from the brain through sensors-either worn on the head like a cap electroencephalography (EEG), placed under the skull electrocorticography (ECoG), or implanted directly into brain tissue. For people with severe paralysis or neurological conditions like ALS, BCIs can restore crucial abilities: enabling communication through thought-controlled typing, operating wheelchairs, or moving robotic limbs. BCIs are medically valuable because they can almost instantly translate brain activity into reliable commands. This speed and precision are vital-in critical care situations, a delay of even half a second in interpreting a "stop breathing machine" command could endanger a patient's life. Medical BCIs must therefore function with near-perfect accuracy to be safe and trustworthy.

The BCI process involves three continuous stages. First, specialized hardware captures the brain's electrical signals like a microphone picks up sound. Next, computer software cleans these signals by filtering out interference from muscle movements or environmental electronics. Finally, decoding algorithms identify meaningful patterns in the purified brain activity, for example, recognizing when a patient imagines moving their left hand, and convert this into device commands. Modern systems accomplish this entire cycle rapidly, often within a second, allowing real-time control. This efficiency transforms medical care: paralyzed patients can now drink water independently using thought-controlled robotic arms, while non-verbal patients can select phrases on communication boards by focusing their attention. Ongoing improvements aim to make these systems more responsive for emergency applications and daily living support.

2.2. Application of BCI in the patients' therapy

2.2.1. Communication restoration

Some BCIs are designed to help people with severe physical disabilities communicate by interpreting their brain signals and converting them into digital commands. These signals can come from different brain-monitoring technologies, such as EEG, ECoG, or intracortical electrodes [3]. For patients who are unable to move or speak-such as those with locked-in syndrome-BCIs offer a

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lifeline by creating a direct communication pathway from the brain to a computer, bypassing damaged muscles and nerves. Users can perform simple tasks like moving cursors, selecting letters, or typing messages.

Recent developments in high-resolution BCIs have enabled users to express more complex thoughts through speech or handwriting decoded from brain activity. For instance, Willett et al. demonstrated that attempted handwriting could be translated into text at speeds of over 90 characters per minute, using intracortical electrodes [4]. Similarly, Moses et al. successfully decoded whole words and sentences directly from the speech cortex, allowing a person with severe speech loss to generate language in real time [5].

In addition to these advanced techniques, hybrid BCIs that combine brain signals with other physiological inputs—like eye movements or residual muscle activity—can enhance reliability. These systems benefit people with progressive diseases, as they can adjust to changing physical abilities. Adaptive algorithms, powered by artificial intelligence, help tailor the system to each individual's brain activity patterns over time. As a result, modern BCIs are becoming faster, more accurate, and easier for users to operate in real-world settings.

Despite their promise, challenges remain. Fatigue, signal noise, and long-term usability must be addressed to ensure consistent communication. Nonetheless, AI, signal processing, and neural engineering innovations continue to push the boundaries of what's possible, bringing us closer to seamless, speech-like interaction for people with the most profound physical limitations.

2.2.2. Sensory feedback restoration

Restoring sensory feedback is essential for naturalistic prosthesis use. Without touch or proprioception, users of robotic limbs must rely almost entirely on vision, often over-gripping objects or barging as a result. Researchers are developing bidirectional BCI systems that convey tactile information through neural interfaces to overcome this limitation. Strategies range from non-invasive skin stimulation to implanted peripheral-nerve or cortical interfaces that inject currents to elicit sensations. For example, Collinger et al. demonstrated that supplementing vision with intracortical microstimulation of somatosensory cortex dramatically improves performance in a tetraplegic subject: trial times on an arm-movement task were roughly halved when artificial tactile percepts were provided [6]. More recently, coordinated multi-electrode stimulation has produced dynamic sensations (e.g., feeling an object's boundary or sliding motion) across a bionic hand's sensory map. These bidirectional approaches yield substantially more natural sensorimotor control and are a focus of active translational research.

2.3. BCIs for rehabilitation phase

As patients enter the rehabilitation phase following severe neurological injuries, restoring consciousness and cognitive engagement becomes as essential as regaining physical movement. BCI technology is emerging as a valuable ally in this delicate process. Rather than waiting passively for signs of awareness to return, BCI systems allow patients to participate, sometimes silently, in their recovery by responding with intention to mental tasks. In a high-quality clinical trial published in the Journal of NeuroEngineering and Rehabilitation, researchers found that stroke patients who received feedback based on their motor imagery, rather than random or passive signals, regained significantly more wrist function and showed stronger communication between brain hemispheres [7].

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For the congenital neurological disability, one of the typical established cases is the genetic pain loss disorder, which results from >20 neurological pathogenic genetic lesions and can cause hereditary sensory neuropathies and congenital insensitivity to pain. These genetic variants lead to hyperactivity of sodium channels, disturbed haem metabolism, altered clathrin-mediated transport, and impaired gene regulatory mechanisms affecting epigenetic marks, long non-coding RNAs, and repetitive elements.

2.3.1. Rehabilitation for neurodegenerative diseases

Biomedical scientists and doctors have invented several standard therapeutic schedules to prevent and treat these disabilities, but the treatment is limited and unreliable. Several disabilities are still incurable and lethal due to the intractable negative impacts and damages they bring to the nervous system, and a compelling example is the neurodegenerative disease. Traditional medical treatment can not effectively reverse the development and effects of diseases such as Alzheimer's disease (AD), Parkinson's disease (PD), Amyotrophic lateral sclerosis, Huntington disease (HD), and Multiple sclerosis (MS). Such diseases are lethal in a sense and pose a significant global health challenge due to their intricate pathology and limited therapeutic interventions. These diseases can be systematically controlled, even cured, by applying the invasive BCIs or using the non-invasive BCIs as a form of conscious training. To sum up, the main application direction of the BCIs for the rehabilitation of neurodegenerative diseases includes:

1. Preservation of Functional Independence through Adaptive Neurorehabilitation

BCI systems enable task-specific cognitive training and assistive device control, actively engaging neural circuits to delay functional decline in conditions like Alzheimer's and Parkinson's. BCIs decode movement intention to drive exoskeletons or functional electrical stimulation (FES) for motor rehabilitation, creating closed-loop neuromodulation. These bypasses damaged basal ganglia pathways in Parkinson's patients, allowing repetitive practice of reaching/grasping tasks, slowing deterioration while promoting use-dependent neuroplasticity.

2. Synergistic Neuroplasticity Enhancement in Parkinson's Rehabilitation

BCI-mediated rehabilitation amplifies neurorestorative effects when integrated with neuroprotective agents (e.g., Mucuna pruriens L-DOPA analogs or curcumin antioxidants). The BCI's real-time feedback loop reinforces dopamine-responsive motor circuits during gait training or balance exercises, while botanical compounds reduce oxidative stress in nigrostriatal pathways. This dual approach maximizes synaptic potentiation, extending periods of functional mobility critical for rehabilitation adherence.

3. Restoration of Social Agency via Assistive Communication/Mobility

As neurodegenerative diseases progress (e.g., ALS, Huntington's), BCIs restore functional communication and environmental interaction through brain-controlled interfaces. Patients operate speech-generating devices (SGDs) or smart wheelchairs using sustained attention or motor imagery, reducing caregiver dependence. This continuous engagement combats social isolation.

2.3.2. Rehabilitation for physical damage causing nervous disabilities

Current prosthetic limbs, while restoring basic mobility for amputees, fail to address the neurological sequelae of physical trauma. Commercial devices lack bidirectional neural interfaces, preventing the transmission of natural sensory feedback (e.g., pressure, proprioception) during object manipulation or ambulation. Consequently, users must compensate through visual/auditory cues—an inefficient process leading to unphysiological gait patterns, unsafe force modulation, and

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secondary health complications (e.g., joint degeneration, phantom pain). These limitations underscore a critical rehabilitation gap: restoring integrated sensorimotor function rather than mere mechanical substitution.

BCI technology represents a paradigm shift in neurorehabilitation by directly interfacing with the nervous system and exploiting the brain's inherent neuroplasticity. These advanced systems demonstrate particular efficacy in detecting and amplifying residual neural signals that often persist below clinical detection thresholds following physical trauma. The technology's unique capacity to establish bidirectional communication between the brain and external devices creates unprecedented opportunities for functional restoration, particularly in cases where conventional rehabilitation approaches have reached their limits. BCIs facilitate a closed-loop rehabilitation process that actively engages the nervous system's adaptive capabilities by translating neural activity into control signals while providing artificial sensory feedback.

The therapeutic potential of this approach was compellingly demonstrated in the landmark study by Biasiucci et al., where BCI systems coupled with functional electrical stimulation (FES) produced significant functional recovery in spinal cord injury patients [8]. This integrated system operates by continuously decoding motor intention and delivering corresponding sensory input, creating an environment conducive to neural reorganization. The intervention capitalizes on Hebbian plasticity mechanisms, where synchronized activation of neural pathways strengthens functional connections through repetitive, task-specific training. Importantly, this BCI-mediated rehabilitation strategy transcends traditional compensatory approaches by directly targeting and reactivating impaired neural circuits, offering the potential for genuine neurological restoration rather than mere functional adaptation. The ability to engage latent neural networks and promote their reintegration into functional systems marks a fundamental advancement in neurorehabilitation, with broad implications for treating various forms of nervous system damage.

3. Challenges and limitations of the BCI's application

Although the BCIs have already been successfully applied in medical treatment and rehabilitation for disabilities that are related to the nervous system's damage and physical disability, there are still some foreseeable negative challenges and limitations to the technique.

3.1. Detected signal variability and noise

Brain signals are often noisy and subject to individual variability. Even under controlled conditions, neural signal quality may fluctuate due to fatigue, attention levels, or electrode positioning. Daly and Wolpaw emphasize that this variability can hinder consistent BCI performance in clinical applications [9]. The noises influence the accurate detection and translation of the target signals, which can cause a failure during transmission and analysis and affect the functional control of the devices.

3.2. Invasiveness vs. accuracy

Invasive BCIs (e.g., intracortical electrodes) offer superior spatial and temporal resolution, allowing for fine-grained decoding of intended motor commands and speech. This precision is especially valuable for applications requiring rapid and nuanced control, such as prosthetic manipulation or real-time communication systems [10]. However, these benefits come at the cost of significant clinical risks. Surgical implantation carries possibilities of infection, scarring, signal degradation

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over time, and potential neural damage. Not all patients are medically eligible or willing to undergo such procedures.

Non-invasive BCIs, typically using EEG, eliminate surgical risks and are more suitable for widespread deployment, especially in vulnerable populations such as patients with neurodegenerative conditions. These systems suffer from low signal fidelity, susceptibility to noise, and limited channel resolution, which constrain their performance in complex tasks. Recent advances in dry electrode technology and AI-based denoising have improved usability, but the accuracy gap between invasive and non-invasive systems remains substantial [11].

3.3. Devise's long-term reliability and maintenance

One underexplored yet critical issue is the durability of BCI components over time. Electrodes, especially in implanted systems, may degrade or require recalibration. According to Raspopovic et al., bidirectional prosthetic systems integrating feedback loops must also account for hardware fatigue and long-term user adaptability [12].

Furthermore, long-term implantation of BCI systems introduces biological and technological challenges that are still being addressed. As Bouton et al. highlighted, chronic implantation of intracortical arrays can result in signal deterioration due to tissue response, gliosis, and electrode encapsulation [13]. These biological reactions diminish device longevity and reliability, limiting their practicality for continuous therapeutic use. Moreover, the absence of standardized long-term maintenance protocols, particularly in home-use environments, complicates sustained user engagement and support.

Addressing these challenges requires innovative biocompatible materials, minimally invasive designs, and robust software strategies for automatic recalibration and error correction. Without these, the long-term viability of BCIs as therapeutic tools remains constrained.

3.4. Scalability and cost

Widespread adoption of BCI systems is constrained by cost, infrastructure, and the need for expert setup. Biasiucci et al. noted that high-quality BCI-facilitated FES remains logistically complex even in successful stroke interventions. Additionally, as emphasized by Lischka et al., personalized tuning of devices to individual neurophysiology adds a further layer of technical difficulty and cost [9].

4. Conclusion

Brain-computer interface technology has demonstrated transformative medical treatment and rehabilitation potential, particularly for nervous system disorders and physical disabilities. As evidenced throughout this review, BCIs have evolved from theoretical concepts to clinically viable solutions addressing critical neurological care challenges. Key applications include communication restoration for locked-in syndrome patients, sensorimotor rehabilitation for stroke and spinal cord injuries, and functional support for neurodegenerative diseases. The success of studies like Biasiucci et al.'s FES-BCI intervention for stroke recovery and Willett et al.'s high-performance handwriting BCI underscores the technology's capacity to restore lost functions through neural pathway reactivation and neuroplasticity enhancement.

However, significant barriers remain for widespread clinical adoption. Technical challenges such as signal variability, invasiveness trade-offs, and long-term device reliability must be addressed through interdisciplinary innovation. Ethical considerations around data privacy, informed consent,

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and equitable access also require urgent attention as BCIs transition from research labs to mainstream healthcare.

Future developments of the BCI should focus on making BCI systems more accessible and user-friendly. Moving from complex, lab-based setups to portable, wearable devices will support broader use in clinical settings and home rehabilitation. Signal processing and machine learning improvements can enhance system adaptability to individual users, making BCIs more efficient and responsive. There is also growing interest in applying BCIs to support mental health, monitor emotional states, and promote neuroplasticity during recovery.

At the same time, ethical considerations such as privacy, informed consent, and equitable access must be addressed. Establishing long-term clinical trials and unified standards will be essential to evaluate BCI systems' effectiveness, safety, and reliability over time. In conclusion, BCIs represent a frontier in medical innovation. Careful development and integration can significantly improve patient outcomes and enable new ways of interacting with the world.

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