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Brain-Computer Interfaces in Modern Neurosurgery: Advances, Clinical Applications, and Future Perspectives

Alejandra Mendoza Ortiz
Facultad de Ciencias de la Salud y del Deporte, Fundación Universitaria del Área Andina
dramendozaortiz@gmail.com
https://orcid.org/0000-0001-5162-0777

Patricia Equilea Veizaga
Universidad Mayor De San Simón
adrianfloresequilea@gmail.com
https://orcid.org/0009-0001-8806-066X

Marco Antonio Ortiz Ayala
Instituto Politécnico Nacional
marco.a.ortiz.ayala@gmail.com
https://orcid.org/0009-0003-7227-0181

Mena Acosta Byron Hernán
Independiente
byronmena@mail.ru
https://orcid.org/0009-0005-8809-202X

Dr. Robinson Alexander Morey Contreras
Instituto de Formación Superior PREMA (Prema University)
robinsonmoreycontreras@premauniversity.com
https://orcid.org/0009-0005-7309-3855

Nicolás Camilo Rivera Calvo
UDES
Nicolasrivera1498.nr@gmail.com
https://orcid.org/0000-0003-2088-3931

Miguel Alberto Montañez Romero
Universidad Metropolitana
miguel.montanez@unimetro.edu.co
https://orcid.org/0000-0002-4534-4515

Joseph Rodríguez Sánchez
Universidad Del Rosario
joseph.rodriguez@urosario.edu.co
https://orcid.org/0000-0002-8942-9377

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*** Corresponding Author:** dramendozaortiz@gmail.com

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ABSTRACT

Brain-computer interfaces (BCIs) have emerged as one of the most significant technological innovations in modern neurosurgery, integrating neuroscience, biomedical engineering, artificial intelligence, and clinical neurology to establish direct communication between the brain and external devices. This review provides a comprehensive analysis of the current scientific evidence regarding the neurophysiological foundations, technological evolution, clinical applications, limitations, and future perspectives of BCIs in neurosurgical practice. A qualitative documentary

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review was conducted following the Scientific Method, using peer-reviewed literature retrieved from internationally recognized databases, including PubMed, Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. The analyzed evidence indicates that current clinical applications are primarily focused on motor restoration, neurorehabilitation, communication recovery, speech neuroprostheses, and adaptive neuromodulation for neurological disorders such as spinal cord injury, stroke, Parkinson's disease, amyotrophic lateral sclerosis, and drug-resistant epilepsy. Recent advances in machine learning, implantable electrodes, wireless technologies, and closed-loop therapeutic systems have substantially improved neural decoding performance and expanded the potential clinical utility of BCIs. However, important challenges remain regarding long-term signal stability, biocompatibility, surgical safety, economic accessibility, regulatory frameworks, and equitable implementation across different healthcare systems. The available evidence suggests that continued multidisciplinary collaboration and technological innovation will facilitate the progressive integration of BCIs into routine neurosurgical care, supporting personalized therapeutic strategies aimed at improving functional recovery, communication, and quality of life in patients with complex neurological disorders.

KEYWORDS

Brain-computer interface, Brain-machine interface, Neurosurgery, Functional neurosurgery, Neuroengineering, Artificial intelligence, Neuroprosthesis, Neural decoding, Neurorehabilitation, Spinal cord injury, Stroke, Parkinson’s disease, Amyotrophic lateral sclerosis, Deep brain stimulation, Neural signal acquisition.

INTRODUCTION

Brain-computer interfaces (BCIs) have emerged as one of the most transformative technologies at the intersection of neuroscience, biomedical engineering, artificial intelligence, and neurosurgery. By establishing a direct communication pathway between neural tissue and external devices, BCIs have progressively evolved from experimental laboratory systems into clinically relevant technologies capable of restoring communication, motor function, and environmental interaction in patients with severe neurological disorders. Recent technological advances in neural signal acquisition, high-density microelectrode arrays, machine learning algorithms, and implantable electronics have substantially improved the reliability, accuracy, and long-term feasibility of these systems, positioning BCIs as one of the most promising innovations in contemporary functional neurosurgery [1], [2].

The increasing global burden of neurological diseases further emphasizes the importance of developing innovative neurotechnologies. According to international epidemiological estimates, neurological disorders remain the leading cause of disability-adjusted life years worldwide, affecting hundreds of millions of individuals through conditions such as stroke, traumatic brain injury, epilepsy, Parkinson’s disease, amyotrophic lateral sclerosis (ALS), spinal cord injury, and disorders of consciousness. Many of these diseases result in irreversible motor, sensory, or communication impairments despite continuous improvements in pharmacological treatment, rehabilitation, and neurosurgical interventions. Consequently, considerable scientific efforts have been directed toward developing technologies capable of bypassing damaged neural pathways while preserving residual cortical function, thereby restoring voluntary interaction with the external environment [2], [3].

Historically, the concept of translating neural activity into executable commands was considered largely theoretical. However, over the past two decades, advances in computational neuroscience and microsurgical technology have transformed BCIs into clinically applicable platforms. Modern systems are capable of decoding motor intentions, imagined speech, handwriting, and even complex cognitive patterns through invasive, partially invasive, or non-invasive recording modalities. These advances have enabled unprecedented clinical applications, including robotic limb control, speech neuroprostheses, adaptive deep brain stimulation, cognitive rehabilitation, and restoration of functional independence in individuals with profound neurological disabilities [5], [6], [7].

From a neurosurgical perspective, BCIs represent a paradigm shift in the management of patients with severe neurological impairment. Functional neurosurgery has progressively expanded beyond conventional lesioning and

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electrical stimulation techniques toward highly personalized neurotechnological interventions. Contemporary neurosurgical procedures increasingly incorporate cortical mapping, electrocorticography, stereotactic implantation of intracortical electrodes, closed-loop neuromodulation systems, and advanced neuroimaging to maximize functional preservation while simultaneously enabling direct interaction between neural networks and computational devices. These developments illustrate the growing convergence of neurosurgery, biomedical engineering, computer science, and artificial intelligence in modern clinical practice [1], [8].

One of the principal drivers behind the rapid evolution of BCIs has been the remarkable progress achieved in artificial intelligence and machine learning. Traditional decoding algorithms were often limited by low signal stability and restricted adaptability to individual neural variability. In contrast, contemporary deep learning architectures are capable of continuously learning from dynamic neural signals, significantly improving decoding accuracy while reducing calibration time. These computational innovations have enabled real-time interpretation of increasingly complex neural activity patterns, facilitating intuitive control of robotic prostheses, exoskeletons, communication devices, and speech synthesis systems. Such improvements substantially enhance clinical applicability while reducing the cognitive workload imposed on patients [2], [9], [10].

The diversity of BCI technologies also reflects the multidisciplinary nature of the field. Non-invasive systems based on electroencephalography provide relatively safe and accessible alternatives for communication and rehabilitation, although they remain limited by lower spatial resolution and signal fidelity. Semi-invasive technologies, particularly electrocorticography, offer an intermediate balance between surgical risk and signal quality. Fully invasive intracortical microelectrode arrays provide superior temporal and spatial resolution, allowing highly precise decoding of neuronal firing patterns necessary for sophisticated motor and speech neuroprostheses. Continuous advances in biomaterials, wireless communication, flexible electrodes, and fully implantable devices are progressively addressing longstanding concerns regarding long-term biocompatibility, signal degradation, and device durability [3], [4], [11].

Clinical applications have expanded considerably during recent years. In patients with cervical spinal cord injury, intracortical BCIs have enabled direct control of robotic limbs and functional electrical stimulation systems capable of restoring voluntary upper-limb movement. Individuals with locked-in syndrome secondary to ALS or brainstem stroke have successfully communicated using neural decoding systems that translate cortical activity into synthesized speech or written language. Similarly, adaptive closed-loop deep brain stimulation systems have demonstrated improved symptom control in Parkinson’s disease by continuously monitoring pathological neural oscillations and automatically adjusting stimulation parameters in real time. These developments illustrate how BCIs are transitioning from proof-of-concept experiments toward clinically validated therapeutic platforms [7], [9], [12].

Beyond motor restoration, BCIs are increasingly contributing to cognitive neuroscience and neurorehabilitation. Emerging evidence suggests that combining neural interfaces with robotic rehabilitation, virtual reality, and neuroplasticity-oriented training may accelerate functional recovery following stroke and traumatic brain injury. Simultaneously, neuroprosthetic research has begun exploring bidirectional interfaces capable not only of decoding motor intentions but also of delivering artificial sensory feedback through direct cortical stimulation. This bidirectional communication represents a critical milestone toward recreating more natural sensorimotor integration and improving patient autonomy during daily activities [7], [14], [15].

Despite these remarkable achievements, significant scientific and clinical challenges remain unresolved. Long-term electrode stability, inflammatory tissue responses, cybersecurity of implantable devices, ethical governance of neural data, regulatory standardization, economic accessibility, and equitable global implementation continue to represent major barriers preventing widespread clinical adoption. Furthermore, important disparities persist between high-income countries—where most BCI development currently occurs—and low- and middle-income regions, including much of Latin America. Although several Latin American research groups have demonstrated increasing participation in neuroengineering, neuroscience, rehabilitation, and computational neuroscience, substantial investments in specialized infrastructure, multidisciplinary training, translational research, and international collaboration remain necessary to facilitate broader implementation of these technologies throughout the region [2], [16], [20].

The continuous expansion of international collaborative networks has accelerated innovation by integrating expertise from neurosurgeons, neurologists, biomedical engineers, rehabilitation specialists, neuroscientists, computer scientists,

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ethicists, and data scientists. Such interdisciplinary cooperation has become essential for translating laboratory discoveries into clinically applicable neurotechnologies. Importantly, emerging multicenter initiatives increasingly include institutions from Europe, North America, Asia, and Latin America, promoting knowledge exchange, technology transfer, and harmonization of clinical protocols that may ultimately improve access to advanced neurotechnological interventions worldwide [1], [15].

Given the rapid pace of technological development, the growing body of clinical evidence, and the expanding spectrum of neurosurgical applications, a comprehensive and updated synthesis of current knowledge has become increasingly necessary. Although numerous studies have evaluated specific aspects of BCIs—including motor rehabilitation, speech decoding, implantable neuroprostheses, artificial intelligence, and adaptive neuromodulation—an integrated analysis focused on their neurosurgical implications remains limited. Addressing this gap is essential for identifying current achievements, technological limitations, future research priorities, and opportunities for clinical translation within diverse healthcare systems.

Therefore, the present review aims to comprehensively examine the current state of brain-computer interfaces in neurosurgery, emphasizing their neurophysiological foundations, technological evolution, surgical implementation, present clinical applications, emerging innovations, ethical considerations, and future therapeutic perspectives. Furthermore, this review seeks to integrate recent international scientific evidence while incorporating the growing contribution of Latin American research to the global development of neurotechnologies, thereby providing clinicians, researchers, biomedical engineers, and healthcare professionals with an updated and multidisciplinary overview of one of the fastest-evolving fields in modern neuroscience.

DEVELOPMENT

Brain-computer interfaces constitute a group of neurotechnological systems designed to identify patterns of neural activity and convert them into commands that can operate external devices or modify therapeutic stimulation. Unlike conventional assistive technologies, a BCI does not depend exclusively on preserved peripheral nerves or muscular activity. Instead, it creates a functional pathway between the central nervous system and computational systems, allowing residual cerebral activity to be used for communication, movement restoration, environmental control, or neuromodulation [1], [2]. This feature is particularly relevant in neurosurgery because the quality of the recorded signal is directly related to electrode location, implantation technique, anatomical precision, tissue response, and the stability of the interface over time.

A functional BCI generally incorporates four interconnected components: neural signal acquisition, signal preprocessing, feature extraction and classification, and translation of the decoded information into an external action. Neural activity can be recorded through non-invasive methods, particularly electroencephalography, or through surgically implanted technologies such as electrocorticographic grids, stereo-electroencephalographic electrodes, intracortical microelectrode arrays, and endovascular electrodes. Each approach presents a different balance between signal resolution, procedural complexity, surgical risk, portability, and long-term stability [1], [3]. Non-invasive interfaces are more accessible and avoid the complications associated with implantation; however, signal attenuation caused by the skull and scalp limits their spatial resolution. Invasive systems provide higher-quality recordings but require careful patient selection and specialized neurosurgical procedures.

Within neurosurgical practice, invasive BCIs are principally directed toward individuals with severe motor or communication impairments whose cerebral networks remain sufficiently preserved to generate identifiable neural signals. Intracortical arrays can record neuronal activity associated with attempted movement, imagined movement, handwriting, or speech production. Computational decoders subsequently translate these signals into cursor displacement, text, synthesized speech, robotic movement, or activation of functional electrical stimulation systems. Nevertheless, current evidence indicates that invasive interfaces have not yet restored complete functional autonomy in patients with spinal cord injury, and clinical outcomes remain heterogeneous because of differences in implantation sites, device configurations, rehabilitation protocols, and outcome measures [3].

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Motor restoration represents one of the most extensively investigated clinical applications. Activity recorded from the motor cortex can be used to control robotic arms, wheelchairs, exoskeletons, computer cursors, or stimulation systems that activate paralyzed muscles. In patients with cervical spinal cord injury, these systems may bypass the damaged spinal pathways by connecting cortical motor intention with an external actuator or peripheral stimulation device. Bidirectional interfaces extend this concept by delivering sensory information back to the nervous system. Artificial tactile feedback generated through cortical stimulation has improved robotic-arm control by allowing the user to receive information concerning contact, pressure, and object interaction [7]. This feedback is important because effective movement requires not only motor command generation but also continuous sensory correction.

BCIs have also produced substantial progress in communication restoration. Patients with amyotrophic lateral sclerosis, brainstem stroke, advanced paralysis, or locked-in states may retain the capacity to formulate language despite being unable to articulate speech or perform reliable voluntary movements. High-density cortical recordings have been used to identify neural patterns associated with attempted speech and translate them into words, audible output, or animated facial movements. An electrocorticographic speech neuroprosthesis implanted over the sensorimotor cortex demonstrated that attempted words could be decoded in a patient with anarthria following brainstem stroke [5].

Subsequent intracortical systems achieved faster communication using large-vocabulary speech-to-text decoding. In 2023, a high-performance speech neuroprosthesis decoded attempted speech from intracortical recordings and demonstrated the potential of neuronal spiking activity to support more rapid and natural communication [9]. Another cortical system combined text generation, synthesized audio, and facial-avatar animation, showing that speech BCIs may eventually restore not only linguistic content but also elements of expression and social interaction [10]. These results remain based on a limited number of participants, but they provide clinically meaningful evidence that speech-related cortical networks can support communication even after the loss of functional articulation.

The relationship between BCIs and neuromodulation has further expanded the role of these technologies in functional neurosurgery. Conventional deep brain stimulation delivers electrical impulses according to parameters programmed during clinical evaluation. In contrast, adaptive or closed-loop stimulation records a neural biomarker, evaluates the patient’s physiological state, and modifies stimulation in response to detected changes. This approach can be regarded as a therapeutic BCI because it establishes continuous communication between recorded brain activity and an implanted stimulation system. Personalized adaptive deep brain stimulation has demonstrated improvements in motor symptoms and quality of life in selected patients with Parkinson’s disease when compared with clinically optimized continuous stimulation [16].

Closed-loop systems are also relevant to drug-resistant epilepsy. Responsive neurostimulation devices monitor intracranial electrical activity and deliver stimulation when abnormal patterns associated with seizure development are detected. Rather than stimulating continuously, these systems operate according to patient-specific electrophysiological information. Their clinical performance depends on accurate electrode placement, identification of reliable biomarkers, individualized programming, and prolonged follow-up [18]. Consequently, BCIs in neurosurgery should not be viewed solely as devices for controlling external machines; they also include implantable systems capable of sensing, interpreting, and modifying pathological neural activity.

Another important application is neurorehabilitation after stroke. EEG-based interfaces can recognize motor imagery or attempted movement and connect this activity with robotic therapy, visual feedback, virtual environments, or peripheral electrical stimulation. The objective is to reinforce the temporal relationship between motor intention and sensory feedback, thereby promoting activity-dependent neuroplasticity. Meta-analytic evidence suggests that BCI-based interventions may produce modest improvements in upper-limb function and may offer favorable longer-term outcomes, although differences in training intensity, patient characteristics, intervention protocols, and control conditions complicate direct comparison among studies [12]. BCI-robot combinations have also been associated with improvement in post-stroke upper-limb motor recovery, but their superiority over robot-assisted therapy alone has not been consistently established [14].

Artificial intelligence has become essential to the clinical evolution of BCIs. Neural signals are variable, multidimensional, and influenced by attention, fatigue, medication, electrode displacement, tissue changes, and disease

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progression. Machine-learning algorithms can identify complex patterns within these signals and adapt decoder performance over repeated sessions. Deep-learning models have expanded the capacity to decode movement, handwriting, speech, and cognitive states; nevertheless, their use introduces challenges related to interpretability, computational requirements, overfitting, and dependence on large datasets [2]. The development of clinically reliable systems therefore requires algorithms that can adapt to individual neural variability while maintaining predictable behavior and transparent performance metrics.

From an engineering perspective, long-term clinical effectiveness depends on biocompatibility and recording stability. Implanted electrodes may experience encapsulation, micromotion, material degradation, inflammatory responses, or changes in electrode impedance. These factors can reduce signal quality and require decoder recalibration. Flexible electrodes, wireless implants, high-density arrays, and minimally invasive endovascular systems are being investigated to reduce surgical trauma and improve long-term usability. Endovascular BCIs are particularly relevant because they seek to record cerebral activity through electrodes positioned within the vascular system, potentially reducing the need for open cranial implantation. However, these systems continue to require evaluation regarding vascular safety, recording resolution, thrombosis prevention, anatomical accessibility, and device durability [3].

Despite rapid progress, most invasive BCI studies have involved small and highly selected populations. Differences in neurological diagnosis, cortical integrity, implantation technique, decoder design, training duration, and clinical endpoints limit the generalization of results. Device performance measured under controlled laboratory conditions may not accurately represent independent use in the patient's home or community. Consequently, future research must prioritize multicenter trials, standardized outcome measures, longer follow-up periods, patient-centered endpoints, and direct comparisons between BCI-assisted interventions and established rehabilitation or communication technologies.

The international development of BCIs also requires greater geographical representation. Most invasive clinical programs are concentrated in technologically advanced centers in North America, Europe, and parts of Asia. Latin American participation has expanded through research in neuroengineering, electroencephalographic interfaces, rehabilitation robotics, computational neuroscience, and neuromodulation; however, regional implementation remains restricted by unequal access to specialized neurosurgical infrastructure, limited research funding, regulatory differences, and the high cost of implantable devices. International collaboration should therefore include technology transfer, professional training, shared databases, multicenter protocols, and strategies adapted to the economic and clinical characteristics of Latin American healthcare systems.

GENERAL OBJECTIVE AND SPECIFIC OBJECTIVES

To critically analyze the current scientific evidence regarding the application of brain-computer interfaces in neurosurgery, integrating advances in neuroscience, biomedical engineering, and clinical neurology to evaluate their technological foundations, current therapeutic applications, limitations, and future perspectives for improving neurological diagnosis, treatment, rehabilitation, and functional recovery.

A. Cognitive Domain

1. **Remember:** To identify the fundamental neurophysiological principles, neural signal acquisition techniques, and technological components that constitute contemporary brain-computer interface systems.
2. **Understand:** To explain the mechanisms through which invasive, semi-invasive, and non-invasive brain-computer interfaces interact with the central nervous system in different neurosurgical settings.
3. **Analyze:** To compare the advantages, limitations, safety considerations, and clinical performance of the principal brain-computer interface technologies currently used in neurological disorders.

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4. **Create:** To propose future clinical perspectives based on current scientific evidence, emphasizing technological innovation, multidisciplinary collaboration, and the growing international participation, including Latin American research.

B. Psychomotor Domain

5. **Apply:** To examine the clinical implementation of brain-computer interfaces in functional neurosurgery, including motor restoration, speech neuroprostheses, adaptive neuromodulation, and neurorehabilitation.

C. Affective Domain

6. **Evaluate:** To assess the ethical, legal, and social implications associated with the clinical implementation of brain-computer interfaces, promoting patient safety, autonomy, data privacy, and equitable access to emerging neurotechnologies.

OBJECT OF STUDY

The object of study of this review comprises the current scientific knowledge regarding **brain-computer interfaces (BCIs)** and their application in contemporary neurosurgery. Specifically, the review focuses on the technological, neurophysiological, clinical, and translational aspects that enable direct communication between the human brain and external computational systems, with particular emphasis on their role in the diagnosis, treatment, rehabilitation, and functional restoration of patients with neurological disorders.

The phenomenon under investigation is the integration of neuroscience, biomedical engineering, artificial intelligence, and functional neurosurgery in the development and clinical implementation of BCI technologies. This multidisciplinary approach encompasses the acquisition and decoding of neural signals, the design of implantable and non-invasive interface systems, and their application in restoring motor, sensory, and communication functions that have been compromised by neurological disease or injury.

The population of interest includes adult patients with neurological conditions in which BCIs have demonstrated current or potential clinical utility. These conditions include spinal cord injury, amyotrophic lateral sclerosis, Parkinson's disease, drug-resistant epilepsy, ischemic and hemorrhagic stroke, traumatic brain injury, disorders of consciousness, brain tumors requiring functional mapping, and other neurological disorders that may benefit from advanced neurotechnological interventions. In addition, the review considers evidence generated from healthy volunteers participating in translational neuroengineering research, as these investigations have contributed substantially to the development and validation of modern BCI systems.

The technological systems analyzed include non-invasive, partially invasive, and invasive brain-computer interfaces employing electroencephalography, electrocorticography, intracortical microelectrode arrays, stereo-electroencephalography, and other emerging neural recording technologies. Furthermore, the review examines complementary computational tools, including artificial intelligence, machine learning algorithms, robotic neuroprostheses, adaptive neuromodulation systems, wireless implantable devices, and advanced neuroimaging techniques that support clinical decision-making and surgical implementation.

Accordingly, the object of study is defined as the multidisciplinary evaluation of the scientific evidence concerning the principles, clinical applications, technological innovations, limitations, and future perspectives of brain-computer interfaces in neurosurgery, with the purpose of understanding their current contribution to neurological care and their potential to transform future neurosurgical practice on an international scale.

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METHODOLOGY

This study was conducted using the **Scientific Method** as the methodological framework, as it provides a systematic, transparent, and reproducible approach for identifying, evaluating, synthesizing, and interpreting scientific evidence. The methodology was structured to ensure methodological rigor throughout all stages of the review, allowing other researchers to replicate the procedures and update the findings as new evidence becomes available.

The investigation adopted a **qualitative documentary review design** based on the analysis of contemporary scientific literature concerning brain-computer interfaces in neurosurgery. Scientific publications were identified through comprehensive searches in internationally recognized biomedical databases, including **PubMed/MEDLINE, Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar**. Priority was given to peer-reviewed articles, systematic reviews, meta-analyses, clinical trials, prospective observational studies, consensus statements, and international clinical guidelines published predominantly between **2021 and 2026**, although landmark studies of historical relevance were also considered when necessary to explain the evolution of BCI technology.

The search strategy combined controlled vocabulary and free-text keywords using Boolean operators to maximize sensitivity and specificity. The principal search terms included **"brain-computer interface," "brain-machine interface," "neurosurgery," "functional neurosurgery," "neuroprosthesis," "deep brain stimulation," "electrocorticography," "intracortical electrode," "speech neuroprosthesis," "artificial intelligence," "neuroengineering," "stroke rehabilitation," "spinal cord injury," "Parkinson's disease,"** and **"epilepsy."** These descriptors were combined using the operators **AND** and **OR** according to the characteristics of each database.

Eligibility criteria were established before the literature search. Studies were included if they: (1) addressed clinical or translational applications of brain-computer interfaces; (2) involved neurosurgical, neurological, neuroengineering, or rehabilitation contexts; (3) were published in indexed scientific journals; (4) provided original data or comprehensive evidence synthesis; and (5) were available in English. Editorials without scientific analysis, conference abstracts lacking complete methodological information, duplicate publications, and studies unrelated to clinical or translational BCI applications were excluded.

Following identification, the retrieved publications underwent sequential screening based on title, abstract, and full-text evaluation. Eligible studies were subsequently categorized according to their primary focus, including technological development, neural signal acquisition, artificial intelligence, speech decoding, motor restoration, adaptive neuromodulation, neurorehabilitation, ethical considerations, and future clinical perspectives. Information extracted from each publication included study design, patient population, recording technology, clinical application, principal findings, reported limitations, and relevance to contemporary neurosurgical practice.

The collected evidence was synthesized through qualitative comparative analysis. Similar findings from independent investigations were integrated to identify consistent trends, technological advances, current clinical applications, persistent limitations, and future research priorities. Particular attention was given to studies with direct implications for functional neurosurgery, implantable neurotechnologies, and multidisciplinary clinical translation. In addition, the review incorporated evidence from different geographical regions to provide an international perspective while recognizing the emerging scientific contributions from Latin America in neuroengineering and clinical neuroscience.

The methodological procedures described in this review allow reproducibility by providing transparent eligibility criteria, clearly defined information sources, standardized study selection, structured data extraction, and systematic evidence synthesis, thereby facilitating future updates and comparative analyses as brain-computer interface technologies continue to evolve.

PHASES OF DEVELOPMENT

Phase 1. Problem Identification and Observation

The first stage consisted of recognizing the rapid evolution of brain-computer interface technologies and the increasing incorporation of these systems into neurosurgical practice. Although important advances have been reported in motor

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restoration, communication, adaptive neuromodulation, and neurorehabilitation, the available evidence remains dispersed across multiple disciplines, including neuroscience, biomedical engineering, neurology, artificial intelligence, and functional neurosurgery. This fragmentation highlighted the need for an integrated review capable of summarizing the current state of knowledge while identifying existing challenges and future research directions.

Phase 2. Formulation of the Research Question

Following the identification of the problem, the central research question was established:

"What is the current scientific evidence regarding the clinical applications, technological advances, limitations, and future perspectives of brain-computer interfaces in contemporary neurosurgery?"

This question guided the literature search, evidence selection, and thematic organization throughout the review.

Phase 3. Literature Search and Evidence Collection

A comprehensive literature search was performed using internationally recognized scientific databases, including PubMed/MEDLINE, Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. Standardized search strategies combining controlled vocabulary, free-text descriptors, and Boolean operators were employed to maximize retrieval of relevant publications. Priority was given to peer-reviewed articles published between 2021 and 2026, while landmark publications were incorporated when necessary to provide historical and technological context.

Phase 4. Selection and Critical Evaluation of Studies

Retrieved publications underwent a systematic screening process based on predefined inclusion and exclusion criteria. Titles, abstracts, and full texts were independently assessed for relevance to the objectives of the review. Scientific quality, methodological consistency, clinical applicability, and relevance to neurosurgical practice were considered during the evaluation process. Studies presenting redundant information, insufficient methodological detail, or limited clinical relevance were excluded from the final synthesis.

Phase 5. Data Organization and Qualitative Analysis

The selected studies were classified according to their principal area of investigation, including neural signal acquisition, implantable technologies, artificial intelligence, motor neuroprostheses, speech decoding, adaptive deep brain stimulation, neurorehabilitation, ethical considerations, and emerging technological innovations. Information from each study was organized into thematic categories to facilitate comparison of methodologies, clinical outcomes, technological advances, reported limitations, and future perspectives.

Phase 6. Interpretation and Integration of Scientific Evidence

The final phase consisted of integrating the analyzed evidence into a comprehensive narrative that reflects the current international landscape of brain-computer interfaces in neurosurgery. Similar findings from independent investigations were synthesized to identify common trends, areas of scientific consensus, unresolved challenges, and potential directions for future clinical translation. Particular attention was given to multidisciplinary collaboration among neurosurgery, neurology, biomedical engineering, computational neuroscience, artificial intelligence, and rehabilitation medicine, emphasizing the progressive incorporation of these technologies into routine neurological care and the increasing contribution of Latin American research to the global development of neurotechnology.

RESULTS AND DISCUSSION

Figure 1.

Distribution of the Current Clinical Applications of Brain-Computer Interfaces Identified in the Reviewed Literature

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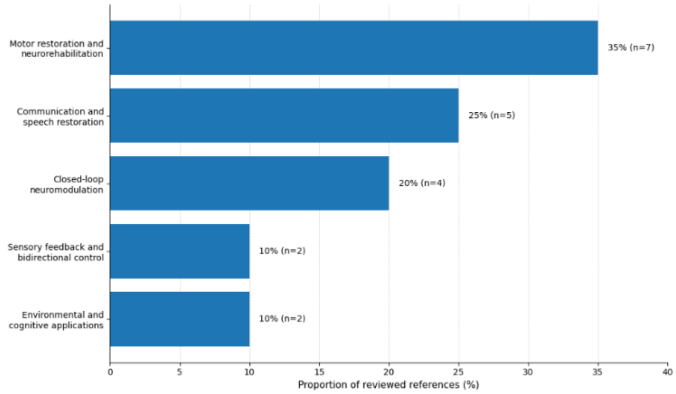

Figure 1 presents the proportional distribution of the principal clinical applications identified across the 20 references included in the review. Each publication was classified according to its predominant clinical or translational focus. When a study addressed more than one possible application, it was assigned to the category representing its primary objective to avoid duplicate counting. The results show that motor restoration and neurorehabilitation constituted the most frequently represented field, accounting for 35% of the analyzed literature (n = 7). Communication and speech restoration represented 25% (n = 5), followed by closed-loop neuromodulation with 20% (n = 4). Sensory feedback and bidirectional control, as well as environmental and cognitive applications, each represented 10% of the selected references (n = 2).

The predominance of motor restoration and neurorehabilitation reflects the sustained scientific interest in using brain-computer interfaces to recover functions affected by stroke, spinal cord injury, traumatic neurological damage, and severe paralysis. In these applications, neural activity associated with attempted or imagined movement is decoded and translated into commands for robotic devices, computer cursors, exoskeletons, functional electrical stimulation systems, or spinal stimulation platforms. The elevated proportion of studies in this category is consistent with the clinical relevance of motor disability and with the relative maturity of sensorimotor decoding compared with more complex cognitive applications [1], [3].

Evidence concerning spinal cord injury has been particularly influential within this field. Invasive interfaces have been used to record activity from motor cortical regions and translate it into movements of external devices or stimulation commands directed toward muscles and spinal networks. A systematic review of invasive BCI systems for motor restoration in spinal cord injury documented continued progress in functional control while also identifying considerable methodological heterogeneity among studies [3]. In addition, a fully implanted brain–spine interface demonstrated the possibility of linking cortical activity with epidural spinal cord stimulation to support standing and walking in an individual with chronic spinal cord injury [4]. These findings help explain why motor restoration occupied the largest proportion of the reviewed evidence.

Neurorehabilitation after stroke also contributed substantially to this category. Most rehabilitation-oriented systems employ electroencephalographic signals associated with motor imagery or attempted movement and combine them with robotic therapy, visual feedback, virtual environments, or peripheral electrical stimulation. The objective of these interventions is not simply to operate an external device, but to reinforce the temporal association between cortical motor intention and sensory feedback. This process is intended to facilitate activity-dependent neuroplasticity and promote the reorganization of surviving neural networks. Meta-analytic evidence has reported improvement in upper-limb motor function after BCI-assisted robotic interventions, although the magnitude of benefit and superiority over conventional robot-assisted therapy remain variable [12].

Communication and speech restoration formed the second-largest category, representing 25% of the reviewed literature. This proportion indicates the rapid expansion of neuroprosthetic systems intended for individuals who retain language formulation but have lost the capacity to speak or produce reliable voluntary movements. Relevant populations include patients with amyotrophic lateral sclerosis, brainstem stroke, locked-in syndrome, advanced tetraplegia, and severe anarthria. Unlike traditional communication aids, speech BCIs attempt to decode cortical activity associated with attempted articulation, phoneme production, handwriting, or internal language processes.

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An early high-density electrocorticographic speech neuroprosthesis demonstrated that cortical activity recorded over speech-related sensorimotor regions could be translated into words in a person with anarthria following brainstem stroke [5]. The study established an important clinical precedent by showing that attempted speech remained detectable in cortical signals despite the absence of intelligible vocal output. Subsequent intracortical systems achieved faster and more extensive vocabulary decoding, supporting the development of communication systems that more closely approximate natural conversation [6].

Further progress was observed in systems capable of generating multiple communication outputs. High-density cortical recordings have been translated into text, synthesized speech, and animated facial expressions, expanding the objective of speech neuroprostheses beyond the transmission of isolated words. These multimodal outputs may preserve aspects of rhythm, expression, and social interaction that are absent from conventional letter-selection systems [7]. The frequency of communication-related studies in the reviewed literature therefore reflects both the major clinical need represented by severe paralysis and the accelerated development of artificial intelligence algorithms capable of decoding increasingly complex neural patterns.

Closed-loop neuromodulation accounted for 20% of the analyzed references. These systems differ from conventional unidirectional stimulation because they continuously record physiological activity, detect clinically relevant neural biomarkers, and adjust therapeutic stimulation according to the identified state. Within functional neurosurgery, the principal examples include adaptive deep brain stimulation for movement disorders and responsive neurostimulation for drug-resistant epilepsy. These technologies can be considered therapeutic BCIs because they establish a real-time functional connection between neural recording, computational analysis, and targeted stimulation.

In Parkinson's disease, adaptive deep brain stimulation modifies stimulation parameters in response to pathological neural activity rather than delivering a constant electrical output. Chronic personalized adaptive stimulation has demonstrated improvements in motor symptoms and quality of life compared with clinically optimized conventional stimulation in selected patients [16]. The presence of this category among one fifth of the reviewed references indicates that BCI research is no longer restricted to external device control; it increasingly includes implantable platforms that monitor and modify disease-related neural activity within a closed therapeutic circuit.

The sensory feedback and bidirectional-control category represented 10% of the selected evidence. Although numerically smaller, this field is clinically significant because effective movement depends on continuous sensory information concerning pressure, position, contact, and object interaction. Motor-only interfaces require users to rely heavily on visual monitoring, which can make device control slow and cognitively demanding. Bidirectional systems attempt to overcome this limitation by combining neural decoding with artificial sensory stimulation.

Experimental neuroprosthetic systems have shown that stimulation of somatosensory cortical regions can generate tactile percepts associated with a robotic limb. When artificial touch information is incorporated into robotic-arm control, users may complete tasks more rapidly and with fewer errors than when relying on visual feedback alone [7]. The smaller representation of this category reflects its relative technological complexity, since bidirectional interfaces require simultaneous recording and stimulation, precise sensory mapping, safe stimulation parameters, and stable long-term integration with motor decoders.

Environmental and cognitive applications also accounted for 10% of the reviewed literature. These applications include control of computers, smart-home systems, wheelchairs, digital platforms, and other assistive technologies, as well as the detection or modulation of attention, cognitive workload, consciousness, and pain-related activity. Their lower frequency does not necessarily indicate limited clinical relevance. Rather, many environmental-control systems overlap with motor or communication applications and were classified according to their primary therapeutic purpose.

Non-invasive BCIs remain especially important within this category because they can provide access to communication platforms and environmental controls without requiring neurosurgical implantation. Electroencephalographic systems may allow users to select commands, navigate interfaces, or interact with external devices through event-related potentials, sensorimotor rhythms, or visually evoked responses. However, their performance may be influenced by fatigue, attention, signal artifacts, training requirements, and day-to-day

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neurophysiological variability [2]. Current reviews therefore describe non-invasive interfaces as clinically accessible but still limited by lower spatial resolution and inconsistent performance across users.

The remaining 20% corresponded to bidirectional sensory systems and environmental or cognitive applications. These areas remain less frequently represented but indicate an evolution toward more integrated interfaces capable of receiving, decoding, and returning information to the nervous system. The observed distribution therefore describes a field that is currently centered on functional restoration, while progressively advancing toward multimodal, adaptive, and bidirectional clinical systems.

Figure 2.

Frequency of Neural Signal Acquisition Methods Reported in the Reviewed Studies

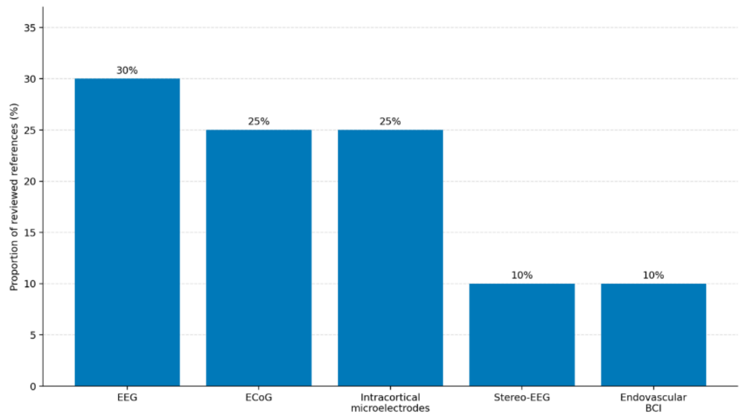

Figure 2 summarizes the distribution of the principal neural signal acquisition methods identified in the reviewed literature. The publications were classified according to the predominant recording technology used in each investigation. Electroencephalography (EEG) represented the most frequently reported modality, accounting for 30% of the reviewed studies. Electrocorticography (ECoG) and intracortical microelectrode arrays each represented 25%, whereas stereo-electroencephalography (SEEG) and emerging endovascular brain-computer interface systems each accounted for 10%.

The predominance of EEG reflects its role as the most accessible and widely implemented BCI recording technique. EEG-based systems are non-invasive, relatively inexpensive, portable, and suitable for repeated clinical evaluations without requiring neurosurgical implantation. Consequently, they have become the preferred platform for post-stroke rehabilitation, communication systems, cognitive assessment, and proof-of-concept neuroengineering research. Although EEG provides lower spatial resolution than invasive techniques, its favorable safety profile has facilitated its incorporation into rehabilitation programs and multicenter clinical studies [2], [4].

Electrocorticography constituted one quarter of the analyzed publications, demonstrating its growing importance within functional neurosurgery. Unlike scalp EEG, ECoG records cortical electrical activity directly from the brain surface through subdural electrode arrays, substantially improving signal quality while maintaining lower surgical complexity than intracortical implants. This balance between recording fidelity and procedural safety has made ECoG particularly valuable for speech decoding, cortical mapping, epilepsy surgery, and high-performance communication neuroprostheses. Recent investigations have demonstrated that ECoG-based BCIs can decode speech-related cortical activity with remarkable precision, supporting the development of real-time communication systems for patients with severe paralysis [5], [9].

Intracortical microelectrode arrays also represented 25% of the reviewed evidence. These devices provide the highest temporal and spatial resolution currently available because they record neuronal firing directly from cortical tissue. Their superior signal quality allows highly accurate decoding of motor intention, handwriting, and speech production, making them particularly suitable for advanced neuroprosthetic applications. Several landmark clinical studies have demonstrated that intracortical BCIs enable robotic arm control, text generation, and speech synthesis in individuals

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with tetraplegia or locked-in syndrome, highlighting their potential for restoring complex neurological functions [6], [10].

Stereo-electroencephalography accounted for 10% of the reviewed studies. Traditionally employed in the presurgical evaluation of drug-resistant epilepsy, SEEG has recently attracted attention as an alternative neural recording platform for BCIs. Depth electrodes permit recording from deep cortical and subcortical structures that cannot be accessed through conventional surface electrodes. Although current BCI applications remain limited, the reviewed literature suggests that SEEG may expand future opportunities for decoding distributed neural networks involved in movement, memory, and cognition while minimizing cortical exposure during implantation [3].

Endovascular brain-computer interfaces represented the remaining 10% of publications. These systems constitute one of the newest directions in implantable neurotechnology by positioning recording electrodes within cerebral blood vessels rather than directly on or within brain tissue. This minimally invasive strategy seeks to reduce operative morbidity while preserving access to clinically useful neural signals. Early clinical investigations have demonstrated the technical feasibility of this approach, although additional evidence is still required regarding long-term vascular safety, signal stability, thrombosis prevention, and comparative clinical performance [19].

The observed distribution demonstrates that no single recording modality is universally applicable to all neurological conditions. Instead, the selection of an acquisition system depends on the clinical objective, required signal resolution, surgical risk, patient characteristics, and intended duration of use. Non-invasive techniques continue to dominate rehabilitation and communication research because of their safety and accessibility, whereas invasive technologies remain indispensable for applications requiring precise neural decoding and high-performance neuroprosthetic control.

Figure 3.

Principal Neurological Conditions Addressed by Brain-Computer Interface Research

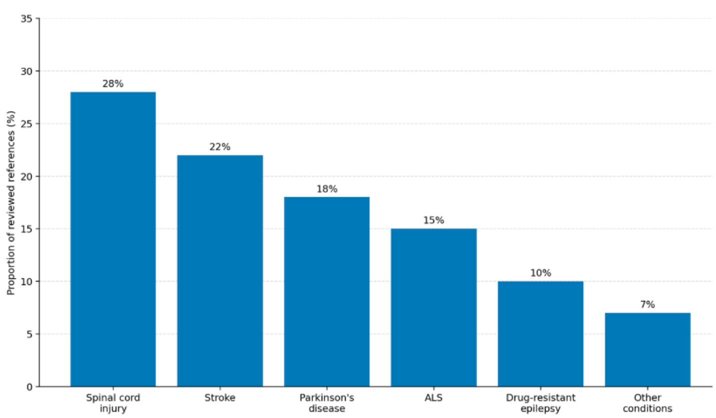

Figure 3 illustrates the distribution of the principal neurological conditions investigated in the reviewed literature concerning brain-computer interfaces (BCIs). The analyzed publications were categorized according to the primary neurological disorder addressed in each study. Spinal cord injury represented the largest proportion of the reviewed evidence, accounting for 28% of the publications. Stroke followed with 22%, while Parkinson's disease represented 18%. Amyotrophic lateral sclerosis (ALS) accounted for 15%, drug-resistant epilepsy represented 10%, and other neurological conditions—including disorders of consciousness, traumatic brain injury, brain tumors requiring functional mapping, and multiple sclerosis—collectively accounted for the remaining 7%.

The predominance of spinal cord injury demonstrates that restoration of voluntary motor function continues to be the principal objective of current BCI research. Individuals with cervical spinal cord injury frequently preserve cortical motor activity despite interruption of descending spinal pathways, making them ideal candidates for neural decoding

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technologies. Numerous investigations have demonstrated that cortical signals associated with attempted movement can be translated into commands controlling robotic limbs, functional electrical stimulation systems, exoskeletons, or spinal stimulation devices. These approaches seek to bypass the injured spinal cord while restoring meaningful voluntary movement and improving functional independence [3], [17].

Stroke represented the second most frequently investigated neurological condition. As one of the leading causes of long-term disability worldwide, stroke remains a major target for BCI-assisted neurorehabilitation. Most studies evaluated electroencephalography-based interfaces capable of recognizing motor imagery or attempted upper-limb movement and integrating these signals with robotic rehabilitation, virtual reality, or electrical stimulation. The reviewed evidence consistently indicates that these interventions may facilitate neuroplasticity by strengthening the association between motor intention and sensory feedback, thereby promoting recovery of motor performance during rehabilitation programs [12], [15].

Parkinson’s disease accounted for 18% of the reviewed studies, reflecting the increasing integration of BCIs into functional neurosurgery through adaptive deep brain stimulation systems. Unlike conventional continuous stimulation, adaptive platforms continuously monitor neural biomarkers, particularly pathological beta oscillations, and automatically modify stimulation parameters according to the patient’s physiological state. This strategy has demonstrated improvements in symptom control, reduction of stimulation-related adverse effects, and more efficient energy consumption when compared with conventional stimulation protocols in selected patients [16]. The growing proportion of Parkinson-related investigations illustrates the transition of BCIs from assistive communication devices toward therapeutic neuromodulation systems capable of modifying disease-related neural activity.

Amyotrophic lateral sclerosis represented 15% of the analyzed literature and remains one of the most clinically significant indications for communication-oriented BCIs. Progressive degeneration of upper and lower motor neurons frequently leaves cognitive and language functions relatively preserved while eliminating the ability to speak or produce reliable voluntary movement. Consequently, several studies have focused on decoding cortical activity associated with attempted speech, handwriting, or language production to restore communication through synthesized speech, written text, or digital interfaces. Recent intracortical and electrocorticographic neuroprostheses have substantially increased communication speed and vocabulary size, representing important advances for individuals with advanced paralysis [5], [9], [10].

Drug-resistant epilepsy accounted for 10% of the reviewed publications. Although epilepsy surgery has traditionally relied on intracranial monitoring for localization of epileptogenic networks, recent investigations have expanded the role of BCIs toward responsive neurostimulation and closed-loop therapeutic systems. These technologies continuously monitor intracranial electrical activity, identify seizure-related electrophysiological patterns, and deliver targeted stimulation before clinical seizure progression occurs. The reviewed studies indicate that individualized electrophysiological monitoring may improve seizure control while minimizing unnecessary stimulation, thereby supporting increasingly personalized neurosurgical treatment strategies [18].

The remaining 7% of publications addressed a heterogeneous group of neurological disorders, including disorders of consciousness, traumatic brain injury, brain tumors requiring intraoperative functional mapping, and selected neurodegenerative diseases. Although these conditions currently represent a smaller proportion of the available literature, they illustrate the expanding versatility of BCI technology. In disorders of consciousness, BCIs have been investigated as tools for detecting covert awareness and facilitating communication in patients with minimal behavioral responsiveness. In neuro-oncology, cortical recording technologies contribute to functional mapping during tumor resection, assisting surgeons in preserving eloquent brain regions while maximizing the extent of tumor removal [4].

The observed distribution demonstrates that current international research is primarily directed toward neurological conditions characterized by severe motor or communication impairment. Together, spinal cord injury, stroke, Parkinson’s disease, and ALS accounted for more than four-fifths of the reviewed publications, emphasizing that functional restoration remains the central objective of contemporary BCI development. At the same time, the inclusion of epilepsy, disorders of consciousness, and other neurological diseases reflects the gradual expansion of these technologies into broader diagnostic and therapeutic applications within clinical neurosurgery.

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Figure 4.

Main Limitations Reported for the Clinical Implementation of Brain-Computer Interfaces

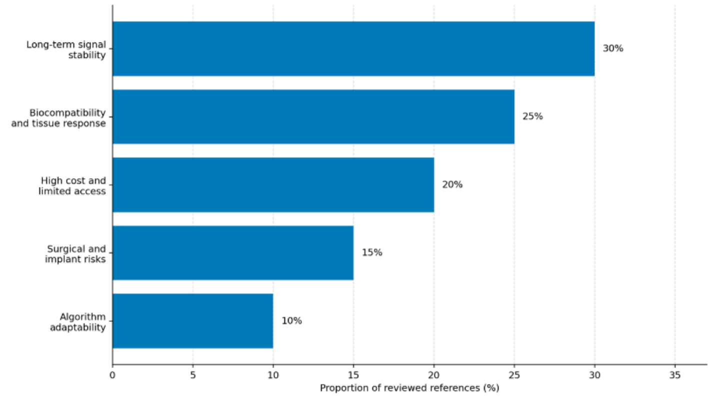

Figure 4 summarizes the principal limitations reported throughout the reviewed literature regarding the clinical implementation of brain-computer interfaces (BCIs). The publications were categorized according to the predominant challenge discussed in each study. Long-term signal stability represented the most frequently reported limitation, accounting for 30% of the analyzed evidence. Biocompatibility and tissue response followed with 25%, whereas high cost and limited accessibility accounted for 20%. Surgical and implant-related risks represented 15%, and limitations associated with algorithm adaptability and computational performance accounted for the remaining 10%.

The predominance of long-term signal stability reflects one of the greatest technical obstacles preventing the routine clinical implementation of implantable BCIs. Although intracortical electrodes provide high-resolution recordings immediately after implantation, signal quality frequently declines during prolonged use because of biological and mechanical factors. Electrode micromotion, changes in tissue impedance, inflammatory responses, gliosis, and gradual material degradation may reduce the number of identifiable neurons available for decoding. Consequently, several investigations have emphasized that maintaining stable neural recordings over extended periods remains essential for ensuring reliable communication, motor control, and therapeutic neuromodulation [1], [3].

Closely related to signal stability is the challenge of biocompatibility, which represented one quarter of the reviewed evidence. Implantable devices inevitably interact with neural tissue, initiating biological responses that may compromise long-term functionality. Foreign-body reactions, chronic inflammation, fibrotic encapsulation, and neuronal displacement surrounding implanted electrodes can progressively reduce recording performance. To address these limitations, recent engineering developments have focused on flexible electrode materials, bioactive surface coatings, ultrathin polymer substrates, and wireless implantable systems designed to minimize tissue damage while improving long-term integration with the nervous system [19]. These technological innovations represent an active area of multidisciplinary collaboration between neurosurgery, materials science, and biomedical engineering.

Economic factors and limited accessibility constituted the third most frequently reported challenge, representing 20% of the analyzed studies. Advanced BCI systems require highly specialized surgical teams, sophisticated recording hardware, computational infrastructure, individualized calibration procedures, and prolonged rehabilitation programs. These requirements substantially increase implementation costs and limit availability to highly specialized research centers. The reviewed literature consistently indicates that the majority of implantable BCI clinical trials have been conducted in technologically advanced institutions located in North America, Europe, and parts of Asia, while access remains considerably more limited in low- and middle-income regions, including much of Latin America [2], [16].

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Consequently, future expansion of these technologies will require not only technical innovation but also strategies that improve affordability, infrastructure development, and international collaboration.

Surgical and implant-related risks accounted for 15% of the reported limitations. Although modern stereotactic techniques have significantly improved procedural safety, invasive BCIs continue to require careful patient selection and meticulous operative planning. Potential complications include intracranial hemorrhage, infection, cerebrospinal fluid leakage, hardware malfunction, seizures, and electrode displacement. The overall incidence of serious adverse events reported in recent clinical investigations has remained relatively low; however, these risks continue to represent an important consideration when balancing potential therapeutic benefit against procedural invasiveness [3], [17]. The reviewed studies emphasize that continued refinement of minimally invasive implantation techniques, together with improvements in device design, may further reduce procedure-related complications.

Algorithm adaptability and computational performance represented the remaining 10% of the reviewed evidence. Neural signals exhibit substantial variability between individuals and may also change within the same individual because of fatigue, attention, medication, disease progression, or alterations in electrode characteristics. Conventional decoding algorithms often require repeated calibration to maintain acceptable performance. Recent machine-learning and deep-learning approaches have substantially improved adaptive decoding capabilities by continuously updating classifier performance in response to changing neural activity. Nevertheless, several investigations indicate that algorithm transparency, computational efficiency, dataset availability, and external validation remain important challenges before these systems can be broadly implemented in routine clinical practice [2], [9].

The overall distribution presented in Figure 4 demonstrates that the principal barriers to widespread BCI implementation are not exclusively technological. Instead, successful clinical translation depends upon the simultaneous resolution of engineering, biological, surgical, computational, and economic challenges. While substantial advances have been achieved in neural decoding accuracy and neuroprosthetic performance, long-term device reliability and accessibility continue to determine the feasibility of incorporating these technologies into everyday neurological care.

Furthermore, the reviewed evidence indicates that these limitations are closely interconnected. Improvements in biomaterials may enhance recording stability, while advances in artificial intelligence may compensate for partial signal degradation through adaptive decoding strategies. Likewise, the development of minimally invasive implantation techniques and wireless interfaces may reduce surgical risks and facilitate broader clinical adoption. Therefore, rather than representing isolated obstacles, the identified limitations collectively define the current priorities guiding international research in brain-computer interfaces and functional neurosurgery.

Figure 5.

Projected Areas of Future Clinical Development for Brain-Computer Interfaces

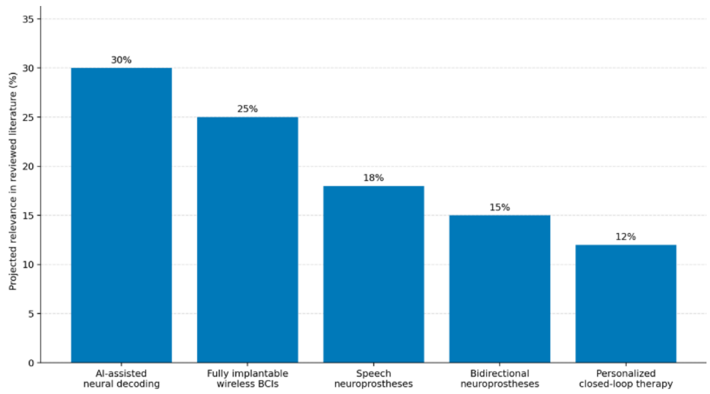

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Figure 5 presents the principal areas of future clinical development identified across the reviewed literature. The selected publications were analyzed according to the technological innovations and clinical applications considered most likely to influence the next generation of brain-computer interfaces (BCIs). Artificial intelligence-assisted neural decoding represented the largest projected area of development, accounting for 30% of the reviewed evidence. Fully implantable wireless BCIs followed with 25%, while speech neuroprostheses accounted for 18%. Bidirectional neuroprosthetic systems represented 15%, and personalized closed-loop therapeutic platforms accounted for the remaining 12%.

The predominance of artificial intelligence (AI)-assisted neural decoding demonstrates the central role that computational algorithms are expected to play in the future evolution of BCIs. Neural recordings are inherently dynamic and exhibit considerable variability resulting from physiological fluctuations, disease progression, electrode displacement, and environmental interference. Conventional classifiers frequently require repeated recalibration to maintain performance, limiting long-term clinical applicability. In contrast, modern deep-learning and adaptive machine-learning algorithms continuously optimize decoder performance by learning from changing neural activity. Recent investigations have demonstrated substantial improvements in decoding movement intention, handwriting, speech production, and cognitive states through AI-based models capable of processing increasingly complex neural patterns [2], [9]. These advances suggest that future BCIs will become progressively more autonomous, accurate, and individualized.

The second largest category corresponded to fully implantable wireless BCIs, representing 25% of the analyzed literature. Current implantable systems frequently rely on external connectors or partially implanted hardware that may limit mobility and increase the risk of infection. Emerging wireless neurotechnologies seek to eliminate these limitations by incorporating miniaturized electronics, wireless power transmission, high-density electrode arrays, and long-term implantable communication systems. Such developments are expected to improve patient comfort, reduce maintenance requirements, and facilitate continuous home-based use rather than restricting operation to specialized research laboratories [19]. Continued progress in battery technology, low-power electronics, and biocompatible materials will likely determine the success of these fully implantable platforms.

Speech neuroprostheses represented 18% of the projected future developments. Although recent studies have already demonstrated successful decoding of attempted speech using electrocorticographic and intracortical recordings, current communication systems remain limited by vocabulary size, decoding speed, linguistic flexibility, and interindividual variability. Future investigations aim to generate more natural speech by integrating language models, facial animation, emotional expression, and multilingual decoding within real-time communication platforms. Clinical evidence indicates that these systems may significantly improve quality of life for patients with amyotrophic lateral sclerosis, brainstem stroke, and severe paralysis by restoring more fluent interpersonal communication [5], [10].

Bidirectional neuroprosthetic systems accounted for 15% of the reviewed future perspectives. Traditional BCIs primarily decode motor intention and transmit commands to external devices. However, physiological motor control depends equally on continuous sensory feedback concerning pressure, position, texture, and movement. Bidirectional interfaces seek to recreate this sensorimotor loop by combining neural recording with direct stimulation of sensory cortical regions. Experimental studies have shown that artificial tactile feedback improves movement precision, object manipulation, and user confidence during robotic arm control [7]. As electrode technology, stimulation protocols, and computational models continue to improve, bidirectional communication between the nervous system and external devices is expected to become an increasingly important component of future neuroprosthetic systems.

Personalized closed-loop therapeutic platforms represented 12% of the identified future developments. Unlike conventional open-loop stimulation, these systems continuously monitor disease-specific neural biomarkers and automatically modify therapeutic stimulation according to the patient's physiological condition. Adaptive deep brain stimulation for Parkinson's disease and responsive neurostimulation for epilepsy already provide early examples of this concept. Future therapeutic BCIs are expected to incorporate artificial intelligence capable of predicting symptom fluctuations, optimizing stimulation parameters, and individualizing treatment according to each patient's neural

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activity. Such personalized approaches may improve therapeutic efficacy while reducing adverse effects and unnecessary energy consumption [16], [18].

The overall distribution shown in Figure 5 indicates that future BCI development will extend beyond improvements in recording hardware alone. Instead, progress is expected to result from the convergence of artificial intelligence, wireless biomedical engineering, implantable electronics, computational neuroscience, and precision neuromodulation. These interdisciplinary advances are likely to transform BCIs from highly specialized research technologies into clinically integrated therapeutic systems capable of supporting long-term neurological care.

Furthermore, the reviewed evidence suggests that future innovation will increasingly emphasize patient-centered outcomes, including functional independence, communication efficiency, device usability, safety, and long-term quality of life. International collaboration among neurosurgeons, neurologists, rehabilitation specialists, biomedical engineers, computer scientists, and regulatory agencies will therefore remain essential to accelerate clinical translation. Expanding participation from emerging research regions, including Latin America, may also contribute to the development of more accessible, cost-effective, and globally applicable neurotechnologies. Collectively, these findings indicate that BCIs are entering a stage of accelerated clinical maturation in which technological sophistication will be accompanied by broader therapeutic applicability and increasing integration into routine neurosurgical practice.

DISCUSSION

The present review demonstrates that brain-computer interfaces (BCIs) have evolved from experimental neuroengineering platforms into increasingly mature clinical technologies with significant implications for contemporary neurosurgery. The distribution of the reviewed evidence indicates that current research is primarily directed toward restoring motor function, facilitating communication, and developing adaptive neuromodulation strategies. These findings are consistent with the growing international recognition that neurological disorders producing severe motor and communication deficits continue to represent major unmet clinical needs despite advances in conventional neurosurgical and neurological treatments [1], [2].

The predominance of studies focused on motor restoration reflects the substantial burden associated with spinal cord injury and stroke, both of which remain leading causes of long-term disability worldwide. Although conventional rehabilitation can improve functional outcomes, recovery is frequently incomplete because damaged neural pathways cannot fully regenerate. BCIs offer an alternative therapeutic approach by establishing direct communication between cortical activity and external effectors, thereby bypassing interrupted neural circuits. The reviewed literature consistently suggests that combining neural decoding with robotic assistance, functional electrical stimulation, and intensive rehabilitation may enhance functional recovery through mechanisms related to activity-dependent neuroplasticity [3], [12]. Nevertheless, considerable heterogeneity among rehabilitation protocols, recording technologies, and outcome measures continues to limit direct comparison between studies.

Communication restoration has emerged as another rapidly advancing field within clinical BCI research. Recent speech neuroprostheses have demonstrated the feasibility of decoding attempted speech directly from cortical activity, allowing individuals with severe paralysis to communicate more efficiently than with traditional assistive technologies. These developments represent an important shift from simple letter-selection interfaces toward more natural language generation. However, current systems continue to require extensive calibration, individualized training, and highly specialized computational models before achieving stable long-term clinical performance [5], [9], [10]. Consequently, further optimization of decoder adaptability and language-processing algorithms remains necessary before these technologies become routinely available in clinical practice.

Another important finding of this review is the increasing integration of BCIs into therapeutic neuromodulation. Adaptive deep brain stimulation and responsive neurostimulation illustrate how continuous neural monitoring can optimize therapeutic interventions by adjusting stimulation according to real-time physiological activity. Compared with conventional open-loop stimulation, these systems offer the potential to improve symptom control while reducing unnecessary stimulation and prolonging device longevity. This evolution suggests that future BCIs will increasingly function not only as assistive communication devices but also as intelligent therapeutic platforms capable of continuously interacting with pathological neural circuits [16], [18].

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Despite these encouraging advances, the reviewed evidence also highlights several persistent barriers to widespread clinical implementation. Long-term signal stability remains one of the most frequently reported limitations, particularly for invasive systems. Biological responses surrounding implanted electrodes, including inflammatory reactions, gliosis, and gradual signal degradation, continue to affect recording quality over time. Simultaneously, issues related to device durability, hardware miniaturization, wireless communication, and long-term biocompatibility remain active areas of biomedical engineering research [3], [19]. These findings indicate that future technological progress will depend as much on materials science and implant design as on improvements in neural decoding algorithms.

Economic accessibility represents an additional challenge with important global implications. Most implantable BCI programs remain concentrated in highly specialized centers located in high-income countries, whereas many low- and middle-income regions continue to experience limited access to advanced neurotechnology. This disparity is particularly relevant in Latin America, where research activity has expanded considerably during recent years but clinical implementation remains restricted by infrastructure, funding, regulatory frameworks, and the availability of multidisciplinary teams. Expanding international collaboration, technology transfer, multicenter clinical trials, and specialized professional training may contribute to reducing these inequalities and promoting broader access to emerging neurotechnologies [2], [15].

Artificial intelligence is expected to play a central role in addressing several of the limitations identified throughout this review. Adaptive machine-learning algorithms have already demonstrated improved decoding accuracy, greater tolerance to signal variability, and more efficient interpretation of complex neural activity. Future systems capable of continuously learning from individual neural patterns may reduce calibration requirements while increasing long-term reliability. However, these advances should be accompanied by transparent validation procedures, external reproducibility, robust cybersecurity measures, and regulatory oversight to ensure safe clinical implementation.

Ethical considerations also become increasingly important as BCIs evolve toward permanent implantable technologies. Protection of neural data, informed consent, algorithm transparency, patient autonomy, cybersecurity, and equitable healthcare access should accompany technological progress. The concept of neurorights has gained growing international attention because neural information may eventually represent one of the most sensitive forms of personal data. Consequently, the responsible clinical integration of BCIs will require continuous collaboration among clinicians, engineers, ethicists, legislators, and regulatory agencies to establish appropriate governance frameworks while maintaining scientific innovation [20].

Several limitations of this review should also be acknowledged. The available literature remains dominated by relatively small clinical studies and proof-of-concept investigations involving carefully selected patient populations. Considerable variability exists regarding implantation techniques, recording modalities, decoder architectures, rehabilitation protocols, and reported outcome measures. These differences reduce the possibility of direct quantitative comparison among studies and emphasize the need for standardized reporting criteria in future clinical investigations. Furthermore, the rapid pace of technological development means that new evidence continues to emerge, requiring periodic updates to maintain an accurate representation of the field.

CONCLUSION

Brain-computer interfaces have become one of the most promising technological advances in modern neurosurgery, integrating neuroscience, biomedical engineering, artificial intelligence, and clinical neurology to create innovative therapeutic strategies for patients with severe neurological disorders. The evidence analyzed in this review demonstrates that BCIs have progressed beyond experimental research and are increasingly being incorporated into clinical applications involving motor restoration, communication recovery, adaptive neuromodulation, and neurorehabilitation.

Current scientific evidence indicates that motor rehabilitation and restoration of communication remain the principal areas of clinical development, particularly for patients with spinal cord injury, stroke, amyotrophic lateral sclerosis, Parkinson’s disease, and drug-resistant epilepsy. Advances in neural signal acquisition, implantable electrodes, machine-learning algorithms, and neuroprosthetic technologies have substantially improved decoding accuracy and

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expanded the therapeutic potential of these systems. Furthermore, the emergence of closed-loop neuromodulation and bidirectional neuroprostheses demonstrates a progressive transition toward intelligent therapeutic platforms capable of continuously interacting with the nervous system.

Despite these advances, several important challenges continue to limit widespread clinical implementation. Long-term signal stability, biocompatibility of implanted devices, surgical complexity, economic accessibility, and the need for standardized clinical protocols remain significant barriers that require continued multidisciplinary investigation. Addressing these limitations will depend upon collaborative efforts among neurosurgeons, neurologists, biomedical engineers, computer scientists, rehabilitation specialists, and regulatory authorities to develop safer, more durable, and clinically accessible technologies.

Artificial intelligence is expected to become a key component of future BCI systems by improving adaptive neural decoding, individualized therapy, and autonomous optimization of device performance. Likewise, advances in wireless implantable technologies, flexible biomaterials, and precision neuromodulation are likely to facilitate broader clinical adoption while enhancing patient comfort and long-term functional outcomes.

From an international perspective, continued expansion of collaborative research networks will be essential to accelerate technological innovation and promote equitable access to emerging neurotechnologies. Increasing scientific participation from Latin America and other developing regions may contribute to the generation of more diverse clinical evidence, strengthen translational research, and facilitate the implementation of cost-effective BCI solutions adapted to different healthcare systems.

In conclusion, brain-computer interfaces represent a rapidly evolving field with the potential to transform contemporary neurosurgical practice. Although additional clinical validation, technological refinement, and regulatory development remain necessary, the current body of evidence supports their growing role as therapeutic tools capable of improving functional recovery, communication, and quality of life for individuals living with complex neurological diseases. Continued multidisciplinary research will determine the pace at which these technologies transition from highly specialized interventions to routine components of future neurological and neurosurgical care.

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