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A Review of Medical Applications of Brain-Computer Interface Technology

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Abstract. Brain–computer interfaces (BCIs) are opening new avenues for treating neurological disorders and physical impairments, yet clinical practice continues to be split between invasive and non-invasive strategies. This work approaches BCI medical applications from three angles: a systematic review of the principal literature, a comparative case analysis contrasting invasive techniques (electrocorticography, microelectrode arrays) with non-invasive ones (electroencephalography, functional near-infrared spectroscopy), and an interdisciplinary assessment that draws together neuroscience, engineering, and ethical perspectives. The findings indicate that invasive BCIs offer strong motor and sensory restoration—for instance, robotic arm control reaching 80–100% task success rates and partial recovery of hand movement—but are limited by surgical hazards, progressive signal deterioration, and price tags above $250,000. Non-invasive BCIs are safer and have seen wider deployment in community-based neurorehabilitation (e.g., around 70% effectiveness for post-stroke upper-limb recovery); nevertheless, they struggle with inherently poor signal-to-noise ratios, a BCI illiteracy rate near 30%, and low information transfer speeds. Current trends spotlight the domestication of non-invasive systems, multimodal sensor fusion, adaptive algorithms, and attempts to clear clinical translation hurdles. Importantly, the assessment reveals mounting ethical and societal strains—neural data privacy, autonomy paradoxes, inequitable access, stigmatization, and military coercion among them. The study stresses the necessity of embedding relational autonomy and neural rights into BCI development, tying technological trajectories to governance demands in order to shape responsible paths for future neurotechnologies.

Keywords: Brain-computer Interface (BCI), medical applications, neurorehabilitation, invasive BCI, non-invasive BCI, neuroethics

1. Introduction

BCI technology has received considerable advancement in the therapy of neurological disorders and physical disabilities, drawing more interest towards its medical applications and potential future developments. In this situation, the current research examines the use and new accomplishments of BCI in the medical field, integrating the progress in both therapeutic and auxiliary aspects. The methodology rests on three pillars: (1) a systematic review of key studies drawn from Google Scholar, IEEE Xplore, and clinical trial registries to identify foundational innovations and emerging

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trends; (2) a comparative case analysis that weighs the clinical efficacy, limitations, and pathways to adoption of invasive and non-invasive BCI techniques [1]; and (3) an interdisciplinary assessment that combines perspectives from neuroscience, biomedical engineering, and ethics to address technical, practical, and societal challenges. The paper also traces the evolution of BCI, categorizes major technologies (e.g., EEG-, ECoG-, and implant-based systems), and maps out future trajectories. It demonstrates the effect of BCI in medicine, ranging from neurorehabilitation to neural prosthetics, and also offers advice on the development and responsible application of next-generation neurotechnologies.

2. Analysis of clinical applications

2.1. Invasive BCI technology

Invasive BCI technology (primarily using ECoG and microelectrodes) has achieved significant progress in clinical efficacy: by directly capturing cortical signals via implanted electrodes, it can restore motor and sensory functions for severely paralyzed patients, including those with spinal cord injury and ALS. Typical cases include precise manipulation of robotic arms (task success rate of 80-100%), restoration of tactile feedback (such as patient perception of external touch), and partial recovery of hand movement function (a paralyzed patient realized independent drinking for the first time after 14 years of paralysis) [2]. However, its limitations lie in surgical risks (infection/tissue damage), long-term signal attenuation (gliosis), and high costs (over $250000), which restrict its widespread adoption. For instance, even a clinical-grade EEG amplifier (e.g., g.tec's g.USBAMP) can cost around $25,000, not to mention the full expense of invasive BCI implantation and maintenance, which puts this technology far beyond the reach of average patients. The application path focuses on functional replacement for severe disabilities, requiring strict surgical indications and postoperative management.

2.2. Non-invasive BCI techniques

Non-invasive BCI (such as EEG, fNIRS) is widely used in rehabilitation medicine due to its safety: clinical efficacy is mainly seen in functional recovery, such as stroke patients improving upper limb function through motor imagery (MI) with EEG combined with VR training (with an effective rate of about 70%), or spinal cord injury patients using fNIRS combined with FES to improve gait [3]. Its prominent limitations include low signal-to-noise ratio (due to skull attenuation), high "BCI illiteracy rate" (affecting about 30% of users who cannot produce effective signals), and limited information transfer rate (SSVEP spelling speed below 20 words/minute) [4, 5]. These limitations make its use more focused on community/home scenarios, with consumer-grade devices such as Emotiv headsets costing less than $1000. Users can operate them after several days of training, but frequent calibration is required to maintain performance [3]. Yet, this frequent recalibration, along with unstable signal quality and a non-negligible risk of user frustration, greatly reduces its usability for long-term home-based rehabilitation, which requires consistent and easy operation.

2.3. Comparative analysis of invasive and non-invasive BCIs

Invasive and non-invasive brain-computer interfaces differ in signal quality, level of clinical evidence, and suitability for various applications. Non-invasive BCIs, commonly based on electroencephalography, are widely used due to their low cost and portability, yet they suffer from

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limited spatial resolution and vulnerability to motion artifacts. Their clinical evidence is strongest for post-stroke upper-limb rehabilitation, where meta-analyses have reported standardized mean differences in Fugl-Meyer Assessment scores ranging from 0.39 to 0.86, and certain devices have obtained FDA clearance. By contrast, evidence for other indications—such as lower-limb rehabilitation, spinal cord injury, and P300-based spellers—remains mostly at the case-series level (Oxford Level 4) without regulatory approval.

Invasive BCIs include microelectrode arrays (e.g., NeuroPort), endovascular stents (e.g., Stentrode), and high-channel-count flexible probes (e.g., Neuralink N1). These devices can capture single-neuron activity or local field potentials with a signal-to-noise ratio roughly 100 times higher than scalp EEG, and have enabled remarkable achievements in motor restoration, speech decoding, and sensory feedback for individuals with severe paralysis. However, these devices face risks such as craniotomy, infection, haemorrhage, device failure, and unknown long-term tissue responses. At present, only responsive neurostimulation for refractory epilepsy and adaptive deep brain stimulation for Parkinson's disease have entered routine clinical practice. The former has meta-analyses showing seizure reductions of 37.9% to 67% and has received FDA approval; the latter has randomised controlled trials demonstrating a 16.3% improvement in most bothersome symptoms over conventional DBS and is also FDA-approved. In summary, non-invasive BCIs are more feasible in low-risk rehabilitation settings, whereas invasive BCIs offer unique, high-fidelity solutions for severe neurological impairments; nonetheless, their broader clinical adoption will require further randomised controlled trials to confirm long-term safety and cost-effectiveness [1]. Clinically, non-invasive BCIs target patients with moderate disability who can actively participate in neurofeedback training, while invasive BCIs are indicated for those with severe, treatment-resistant disabilities who need precise, high-bandwidth neural control despite higher procedural risks.

3. Current research and development trends

The current trend in BCI R&D is the increasing use of non-invasive technologies, for example, moving EEG systems to ALS patients' home environments to improve portability and anti-interference. Other trends include the rise of NIRS as a low-cost metabolic signaling solution, the development of multimodal fusion and adaptive algorithms that integrate EEG and eye-movement signals and use dynamic models, and breakthroughs in application scenarios such as robotic arm control and FES limb function reconstruction. EEG-BCI deeply integrates smart home and environment interaction [6]. Researchers are also using real-time fMRI/EEG feedback to induce cortical reorganization in neurological rehabilitation, and they are working on clinical translation bottlenecks, such as long-term stability of invasive electrodes, open-source frameworks, and standardised protocols. These efforts aim to transform BCI from laboratory tools to medical devices through interdisciplinary collaboration (neuroscience, engineering, and clinical medicine), and to balance safety, practicality, and efficacy [7].

Despite this progress, the real-world deployment of EEG-based BCI systems still faces several limitations [8]. Signal quality is compromised by inherent non-stationarity and artefacts, with no universal denoising algorithm performing reliably across scenarios, especially when channel numbers are reduced for portability. Hardware remains user-unfriendly: wet electrodes are cumbersome, dry electrodes yield inferior performance (e.g., 30% lower information rates), and device standardisation is lacking. Information transfer rates are generally low for P300 and motor imagery paradigms, while SSVEP induces visual fatigue, and motor imagery demands lengthy calibration [8]. Deep learning models suffer from poor cross-session generalisation and high computational cost, hindering real-time use; Riemannian classifiers face unresolved stability

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challenges. Evaluation metrics are heterogeneous across studies, complicating direct comparisons. Clinical validation is weak, as most tests involve healthy volunteers rather than target patients, whose performance is markedly worse, and long-term neural effects are unknown. Commercialisation is obstructed by high costs, reliance on expert assistance, insufficient environmental robustness, and absence of fail-safe mechanisms. Addressing these issues is essential for BCI to become a dependable and widely accessible technology.

4. Ethical, societal considerations, and future directions

The rapid development of brain-computer interface technology has brought significant ethical and social challenges. On an ethical level, there is a contradiction in autonomy: BCI not only benefits individuals with mobility impairments, but may also undermine their decision-making autonomy. Identity recognition faces the risk of alienation, and users' perception of technology is polarized; The privacy and security risks are prominent, and brain signals are easily stolen and manipulated, making it difficult for existing laws to address the specificity of neural data; There is great controversy over responsibility attribution and research ethics, including unclear accountability for technology abuse, as well as ethical issues such as informed consent for vulnerable groups and commercial animal experiments [9].

The dilemma of fairness is prominent, with high priced BCI devices excluding the disabled population, and the commercialization of cognitive enhancement technology exacerbating class differentiation; Stigmatization is evolving dynamically, and BCI devices may become new objects of discrimination, but widespread adoption may also reshape disability cognition; Military applications have raised special ethical issues, such as coercion of soldiers for neural enhancement and regulatory arbitrage driven by US-China technological competition [10].

At the technical level, innovations such as biodegradable neural chips and flexible electrodes enable non-invasive monitoring and safety upgrades, while closed-loop perception feedback and brain-to-brain communication networks promote the development of human-machine symbiosis. At the level of ethical governance, it is necessary to establish a neural security defense system, legislate to protect brain privacy rights, promote inclusive policies, and strengthen cross-border cooperation to curb regulatory arbitrage and promote the implementation of the Neural Rights Charter; At the level of social integration, BCI is evolving towards a "neurooperating system", and in this process, it is necessary to guard against data monopolies of neurocapitalism and establish a user led data governance model. As Livanis emphasizes, only by balancing technological innovation and ethical norms within a relational autonomy framework can BCI truly become a tool that empowers people, rather than a risk of alienating them [11].

5. Conclusion

This review maps the dual-track reality of medical BCI: invasive approaches (ECoG, microelectrode arrays) deliver highly effective motor and sensory restoration for severe paralysis but are constrained by surgical risk, long-term signal degradation, and costs over $250,000; non-invasive approaches (EEG, fNIRS) enable safe, community-based neurorehabilitation with ~70% effectiveness in post-stroke recovery yet remain hindered by low signal-to-noise ratio, an ~30% BCI illiteracy rate, and slow information transfer. Current trends center on the growing use of non-invasive systems, multimodal fusion, adaptive algorithms, and efforts to overcome barriers to clinical adoption. Critically, escalating ethical tensions—neural data privacy, autonomy paradoxes, equity barriers, stigmatization, and military coercion—demand embedded governance.

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Future research should focus on: (1) improving non-invasive signal fidelity and reducing BCI illiteracy through advanced sensors and hybrid paradigms; (2) developing minimally invasive or biocompatible electrodes that ensure long-term stability; (3) conducting large-scale randomized controlled trials to solidify clinical evidence and cost-effectiveness; (4) constructing robust neural-rights frameworks, privacy-preserving architectures, and inclusive policies that embed relational autonomy, and steer BCI toward responsible, equitable neurotechnology.

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