# Brain–Computer Interfaces at a Crossroads: A Critical Analysis of Technical, Ethical, and Societal Hurdles on the Path to a Connected Future

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## Abstract

Brain–computer interfaces (BCIs) are rapidly transitioning from niche clinical tools to powerful technologies with the potential to reshape human–machine interaction, cognitive agency, and social structures. Initially developed to restore communication and motor function in individuals with severe neurological impairments, recent advances have expanded BCI applications into neurorehabilitation, mental health, and commercial domains, raising profound technical, ethical, and societal challenges. Here we critically examine the current state of BCI development, arguing that the field has reached a pivotal inflection point. Beyond engineering performance, unresolved issues, including long-term biocompatibility, decoding reliability, neural data privacy, identity and autonomy, regulatory gaps, and social equity, now constitute the primary barriers to responsible deployment. We contend that technological progress alone is insufficient to ensure beneficial outcomes and that the future trajectory of BCIs will be determined by the integration of robust ethical frameworks, inclusive governance, and long-term societal foresight. By synthesizing recent clinical breakthroughs with emerging ethical and regulatory concerns, we advocate for a precautionary yet forward-looking approach that prioritizes human dignity, safety, and equitable access alongside innovation. The choices made at this juncture will shape whether BCIs ultimately serve as instruments of empowerment or sources of new vulnerability in a deeply interconnected future.

**Keywords:** brain–computer interface, neurotechnology, neuroethics, neural decoding, human–machine interaction, data privacy

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## Introduction

The evolution of brain-computer interfaces (BCIs) has accelerated dramatically, fueled by converging advances in neuroscience, materials science, machine learning, and microfabrication. Initially conceived as a communication lifeline for severely paralyzed individuals, the scope of BCI applications has expanded into neurorehabilitation (e.g., stroke recovery)[1, 2], treatment of neuropsychiatric disorders (e.g., deep brain stimulation for obsessive-compulsive disorder (OCD))[3], and commercial ventures in gaming and wellness[4]. High-profile demonstrations, such as intracortical implants enabling tetraplegic users to control digital cursors or robotic prostheses with increasing dexterity, have captured global attention and investment.

However, this very expansion is the source of both excitement and acute concern. The narrative is rapidly shifting from merely restoring function to actively augmenting capability. We posit that the field now stands at a critical inflection point. The path forward is bifurcated: one leading toward a future of democratized cognitive and physical empowerment, the other toward exacerbated inequalities, novel forms of vulnerability, and uncharted threats to personal identity. To navigate this juncture, a clear-eyed assessment of present limitations and future implications is not just academic, it is an urgent societal imperative.

This commentary is based on a comprehensive review of peer-reviewed literature, clinical trial registries, and strategic policy documents published between 2021 and 2026. We systematically searched major databases, including PubMed, Google Scholar, and IEEE Xplore, using targeted keywords such as "BCI" "neural decoding," "neuroethics," and "implantable neurotechnology." The "major breakthroughs" highlighted in this analysis were selected based on three primary criteria: clinical validation, industrial scalability, and global strategic impact.

Specifically, we focused on recent (2024–2026) first-in-human trials demonstrating tangible functional restoration, such as the Stanford inner speech study and the "BeiNao-1" clinical trials. Furthermore, we prioritized developments signifying a shift from laboratory prototypes to mass production and automated surgical deployment, most notably the 2026 Neuralink production roadmap. Finally, we selected milestones that illustrate the international diversification of BCI development, focusing on the intersection of technical advancement and national policy in the United States and China. By synthesizing high-impact peer-reviewed research from journals such as *Cell and Nature Biomedical Engineering* with verified industry reports, this analysis aims to provide a holistic view of the BCI landscape at its current inflection point.

## Three recent major breakthroughs

BCI technology is no longer a product of science fiction but is demonstrating tangible value in clinical validation. Whether restoring motor function, reconstructing vision, or decoding inner speech, these cases represent the cutting-edge breakthroughs in the field. Before examining individual systems in detail, Table 1 provides a technical comparison of the major BCI platforms discussed in this manuscript, highlighting their distinct engineering approaches, implantation paths, and surgical requirements. This comparison reveals that "BCI" encompasses a diverse family of technologies with fundamentally different risk-benefit profiles, a theme we explore throughout this analysis.

### *Neuralink's clinical progress and production plans*

Neuralink has emerged as a prominent player in the BCI landscape, with the company reporting significant clinical expansion. According to company disclosures, 12 patients with severe paralysis had received Neuralink implants as of September 2025, enabling them to perform tasks like playing games, browsing the internet, and controlling robotic arms[5, 6]. Neuralink's president has stated that the company aims to implant its devices in 20,000 people annually by 2031 and eventually expand to applications in healthy individuals, though clinical partners emphasize the company remains "a long way" from this goal[6].

In a peer-reviewed editorial published in Expert Review of Medical Devices, Kumar and colleagues contextualize Neuralink's contributions within the broader

**Table 1: Technical comparison of major BCI systems.**

| Feature | Neuralink | BeiNao-1 | Stanford inner speech |
|---|---|---|---|
| Implantation path | Intracortical (penetrates brain parenchyma) | Epidural (on skull surface, electrodes outside dura) | Intracortical (penetrating arrays in research participants) |
| Brain contact | Direct penetration of neural tissue with flexible threads | Electrodes placed on dura mater; no brain tissue contact | Direct penetration of neural tissue with existing arrays |
| Electrode type | Microwire (polymer threads with gold electrodes, 4–6 μm thread width) | electrocorticography (ECoG) array (electrode contacts on flexible substrate) | Utah array or similar penetrating microelectrode arrays |
| Surgical procedure | Craniotomy (8 mm diameter); robotic insertion of 128 threads at 1.5 seconds per thread | Minimally invasive drilling; epidural placement without dural penetration | Craniotomy with manual insertion (performed prior to study enrollment) |
| Invasiveness level | Highest (brain tissue penetration, foreign body response) | Moderate (skull penetration, but dura mater remains intact) | Highest (brain tissue penetration from prior implantation) |
| Foreign body response risk | High (glial scarring, neuronal death, signal degradation over months–years) | Low (dura protects brain tissue; reduced immune response) | High (established risk from chronic penetrating implants) |
| Advantages | Highest information content; precise decoding of complex movements | Reduced immune response; potentially better long-term stability; no brain tissue damage | Proven research platform; enables investigation of higher-order cognitive processes |
| Limitations | Signal degradation over time due to glial scarring; complex explantation surgery | Cannot isolate single neurons; lower spatial resolution than intracortical | Not designed as permanent therapeutic implant; requires existing implanted arrays |
| Development stage | Commercial device; 12 patients implanted as of September 2025; *The New England Journal of Medicine* (*NEJM*) manuscript under review | Clinical trial; 5 patients implanted as of early 2026; peer-reviewed outcomes pending | Research study; published in Cell (August 2025) with 4 participants |

landscape of brain–machine interface research spanning over six decades[7]. They note that while Neuralink's flexible microelectrode arrays containing 3,072 electrodes represent a significant engineering achievement, building on foundational work including the Utah Array (96 channels), electrocorticography grids, and Neuropixel devices, the number of electrodes alone does not define performance, as signals must be meaningful and stable over time. The authors highlight Neuralink's robotic insertion system, which achieves micron-level accuracy with minimal vascular disruption, but caution that issues like electrode displacement, as recently reported in Neuralink's first human trial, underscore the need for careful long-term assessment to faithfully replicate neural signaling and enhance BCI fidelity[7].

In a significant step toward independent scientific validation, Neuralink has submitted its first peer-reviewed manuscript to *The New England Journal of Medicine* describing results from its first three patients, including safety data and performance metrics. This submission, confirmed by clinical trial site principal investigators, marks the company's first effort to publish human data in a peer-reviewed forum[8]. However, as of this writing, the manuscript remains under review, and the data has not yet been published or independently verified. The company has also announced intentions to begin large-scale device production in 2026, moving toward streamlined and automated surgical processes[9].

## China's "BeiNao-1" system: semi-invasive BCI progress

In China, significant advances have been reported with semi-invasive BCI technology. The "BeiNao-1" system, developed through collaborative research efforts, employs a semi-invasive approach with electrodes placed epidurally on the skull surface, avoiding direct penetration of brain tissue[10, 11]. This design theoretically reduces risks associated with immune response and scar tissue formation compared to fully invasive intracortical arrays[11].

According to press reports and institutional announcements, the first-in-human trial of the integrated BeiNao-1 system was initiated in 2025, with multiple

patients successfully implanted[10, 11]. News reports describe patients with spinal cord injury using the system to control robotic arms and rehabilitation equipment through thought alone[10]. As of early 2026, reports indicate that five patients have received the implant, with a sixth implantation scheduled[11].

A peer-reviewed article by Jizong Zhao, a neurosurgeon involved with the BeiNao-1 project, was published in *The Medical Journal of Peking Union Medical College Hospital* in 2025, providing authoritative context on the system's design principles and acknowledging research funding for the "Beinao-1 Intelligent Brain-Core System"[12]. However, detailed clinical outcomes data from these trials have not yet appeared in peer-reviewed publications and remain available only through media reports and institutional announcements.

The "quasi-practical" classification of semi-invasive systems such as BeiNao-1 warrants explicit comparison with fully invasive approaches regarding signal quality. Research comparing epidural, subdural, and endovascular recordings has demonstrated that signal-to-noise ratio (SNR) and bandwidth of epidural signals are not significantly different from conventional intracranial sensors[13]. This finding is critical: the dura mater, while providing a protective barrier that reduces immune response and scar tissue formation, does not substantially degrade signal quality for field potential recordings.

However, important tradeoffs exist. Intracortical penetrating arrays (e.g., Neuralink's microwires) achieve single-neuron resolution with action potential ("spike") detection, enabling decoding of complex motor intentions. Epidural recordings capture local field potentials (LFPs) and electrocorticographic (ECoG) signals with spatial resolution sufficient for motor rehabilitation and basic speech decoding, but cannot resolve individual neuron activity. Thus, the "quasi-practical" designation reflects this optimized balance: sufficient signal fidelity for therapeutic applications with substantially reduced long-term biocompatibility risks.

## Stanford's inner speech decoding

Stanford's Inner Speech Decoding represents a major breakthrough for BCI technology in the field of communication. The research, published in the journal *Cell* in August 2025, demonstrated the ability to extract information from decoded inner speech[14]. The team found that the patterns of brain activity triggered by inner speech are similar to, though smaller than, those elicited when attempting to speak aloud. They also developed a passcode protection system to prevent the accidental decoding of unintended inner thoughts with greater than 98% accuracy. This work has undergone full scientific peer review and is publicly available for independent evaluation.

The cases presented above involve patients with severe neurological impairments, yet standardized functional outcome measures are inconsistently reported across studies. Table 2 summarizes available clinical data from key trials and case reports discussed in this manuscript, highlighting both achievements and gaps in functional assessment.

## The industry inflection point

The year 2025 marked a historic turning point for BCI technology. Having progressed from assisting paralyzed patients with communication to restoring basic motor functions, the technology is rapidly transitioning from the laboratory to commercial application[15]. Dozens of patients globally have been implanted with various BCI devices. Scientists at Stanford University have even succeeded in detecting the inner speech of patients with speech disorders through a BCI. Meanwhile, the success of China's first semi-invasive BCI human trial established it as the second country worldwide, after the United States, to master and conduct such human experiments[10, 11], signifying a critical catch-up in technological development. The year 2025 is regarded as the "first year" of BCI development in China. Seven ministries, including the Ministry of Industry and Information Technology (MIIT), jointly issued the Implementation Opinions on Promoting the Innovative Development of the Brain–Computer Interface Industry, outlining a roadmap for industrial growth[16]. The national "15th Five-Year Plan" proposal lists "brain–computer interface" as one of the six major directions for future industries, confirming its strategic importance in China. Local policy support quickly ensued[17]. Beijing established a 300 million yuan brain science

**Table 2: Clinical outcomes and functional measures in representative BCI cases.**

| Study/system | Patient population | Number of patients | Key functional outcomes | Functional scales used | Limitations/notes |
|---|---|---|---|---|---|
| Neuralink PRIME study | Tetraplegia (severe paralysis) | 12 (as of September 2025) | Cursor control for computer interaction<br>Internet browsing capability<br>Gaming (MindPong demonstrated)<br>Robotic arm control | Study-specific performance metrics; peer-reviewed data pending | Manuscript under review at NEJM; detailed functional data not yet publicly available; first 3 patients described in submitted manuscript |
| BeiNao-1 | Spinal cord injury; speech impairment | 5 (as of February 2026) | Robotic arm control for grasping objects<br>Control of rehabilitation equipment through thought<br>Motor function substitution reported | Not reported in available sources | Detailed clinical outcomes pending peer-reviewed publication; information from press reports only |
| Stanford inner speech[14] | Paralysis (amyotrophic lateral sclerosis (ALS), brainstem stroke) | 4 | Decoding accuracy up to 74% for 125,000-word vocabulary<br>Passcode protection system > 98% accuracy<br>Real-time inner speech decoding demonstrated | Study-specific accuracy metrics; no standardized functional scale reported | Primary outcome was decoding accuracy, not activities of daily living; all patients had prior existing implants |

and BCI incubation fund to support early-stage projects and innovative enterprise incubation in the field[18]. Shanghai launched the nation's first BCI future industrial cluster, "Brain-Tech Valley"[19, 20]. By the end of 2025, Chinese company NeuroXess had completed 54 human implants of its BCI devices[21], and Stair Medtech released its second-generation 256-channel wireless implantable BCI system, which quadrupled the signal channels from 64 in the first generation while keeping the implant size largely unchanged[22].

## Challenges and future directions

While media often highlights BCI "miracles," the day-to-day reality for researchers and users is defined by persistent technical constraints that hinder reliability, scalability, and long-term use.

### The biocompatibility bottleneck

Invasive BCIs, which offer the highest signal fidelity, engage in a continual damaging battle with the immune system. The foreign body response leads to glial scarring, neuronal death, and electrochemical degradation around implanted electrodes, causing signal quality to decay over months or years[23]. While novel materials (e.g., bioactive coatings, flexible "neurograins") promise improvement, a truly stable, life-time neural interface remains elusive. This durability challenge directly impacts the risk-benefit calculus for non-life-threatening applications.

### The decoding dilemma

Current BCIs largely rely on decoding motor intent or low-level signals. Translating the nuanced tapestry of higher-order cognitive processes, abstract thought, emotion, and intentional deception, into machine commands is a problem of staggering complexity. Machine learning models are often "black boxes" trained on limited, user-specific data, suffering from poor generalization and vulnerability to neural "noise" from fatigue, stress, or unrelated mental activity[24]. Achieving truly intuitive, context-aware control requires a fundamental leap in our ability to model and interpret the brain's dynamic, networked activity.

### The bandwidth chasm

The human brain processes information at a rate orders of magnitude higher than any current BCIs can interpret or transmit[24]. This bottleneck creates a latency that

disrupts the sense of real-time agency, a phenomenon known as the "uncanny valley" of control. For augmentation applications, this chasm is even more pronounced; enhancing sensory input or cognitive throughput would require bidirectional interfaces with massive, safe data exchange capabilities, a frontier still in its infancy.

## The ethical labyrinth: privacy, agency, and equity

The technical challenges, while formidable, may be solvable through engineering. The ethical and societal implications pose questions for which we lack consensus, precedent, or adequate policy. Recent real-world cases illustrate that these concerns are not merely hypothetical but are already emerging in clinical and commercial settings.

### Neural privacy as a fundamental right

Neural data is not merely another data stream; it is a direct window into a person's thoughts, emotions, and predispositions. Current data protection regulations (e.g., general data protection regulation (GDPR)) are ill-equipped to address the unique sensitivity of this information. Threats range from commercial exploitation (e.g., targeted neuromarketing) to state-level surveillance, and even include risks like "neuro-hacking"[25]. Establishing the principle of neuronal integrity and developing cryptographic techniques for neural data are paramount.

A landmark case from Chile in 2023 illustrates this vulnerability. Former senator Guido Girardi purchased and used an Insight wireless electroencephalography (EEG) device from the neurotechnology company Emotiv, which collects brain data to interpret emotions and execute mental commands. A critical issue emerged: users could access their own brain data only by purchasing a "Pro" license. With the free license Girardi selected, his brain data remained inaccessible to him but were stored in the company's cloud system and, according to privacy policies, could be transferred to third parties. On August 9, 2023, the Supreme Court of Chile ruled in Girardi's favor in the first successful lawsuit against a consumer neurotechnology company for violating brain data privacy, finding that Emotiv had infringed his rights to privacy and psychological integrity under Chile's constitution[26]. This case establishes a critical precedent: brain data cannot be treated as just another commercial asset.

Another concerning privacy breach emerged from unexpected sources. Researchers at the Mayo Clinic demonstrated that facial recognition software could successfully identify research participants from de-identified magnetic resonance imaging (MRI) images. In an experiment published in *The New England Journal of Medicine*, Schwarz and colleagues recruited 84 volunteers and found that commercial facial recognition software correctly matched MRI-constructed faces to photographs for 83% of participants, with 95% correctly identified among the top five choices[27]. As one expert noted, "Someone with access to de-identified MRIs from a research study and a belief or suspicion that a specific individual's images may be contained in that study, could potentially identify that individual"[27]. This finding reveals that brain data, even when ostensibly anonymized, may be re-identifiable through AI-powered tools, raising profound questions about the adequacy of current data protection standards.

The recognition of these emerging threats has spurred policy action, with jurisdictions like California enacting specific neurorights legislation. However, as a comprehensive analysis in Neuroethics highlights, translating the concept of neurorights into effective legal and regulatory reality presents profound challenges. These include navigating legal fragmentation between different countries' laws, ensuring enforcement against powerful transnational technology companies, and carefully balancing novel neurorights against other fundamental rights, such as freedom of speech or scientific inquiry[28]. Furthermore, determining appropriate remedies for violations, from data misuse to the manipulation of mental states, and creating oversight mechanisms for both state and non-state actors remain unresolved hurdles. Thus, while establishing principles like neuronal integrity is paramount, their successful implementation demands not just new laws, but the development of sophisticated, adaptive, and internationally coordinated regulatory frameworks.

### Identity, autonomy, and the blurring of self

BCIs that modulate mood (e.g., for depression) or enhance cognitive focus directly intervene in the biological underpinnings of personality and agency. When a decision is influenced by a neuroprosthesis, who is the author, the human, the algorithm, or the corporation that tuned it? This challenges legal and philosophical concepts of responsibility and selfhood[29].

In the Embodiment and Estrangement study, the ethical dimensions of identity, autonomy, and the blurring of self-emerge as central concerns in the use of BCIs. Participants reported both empowering experiences of embodiment, where the device felt integrated into their sense of self and enhanced agency, and unsettling experiences of estrangement, where the technology disrupted their identity and created feelings of disconnection. These dual outcomes highlight that BCIs are not merely functional tools but interventions that reshape how individuals perceive themselves and their autonomy. Ethically, this raises questions about consent, psychological well-being, and the preservation of personal identity, underscoring the need for safeguards that ensure BCIs enhance rather than compromise the integrity of the self[30].

Furthermore, the potential for "brainjacking" or unauthorized manipulation of neural devices presents a terrifying new form of violation. Legal scholars have raised concerns about covert neural interfaces: BCIs deployed without the knowledge or consent of the subject, potentially designed to avoid detection[31].

### The specter of a neuro-social divide

The high cost of advanced BCI technology risks creating a new axis of inequality: a class of "neuro-enhanced" individuals with cognitive, educational, or professional advantages, and an "unplugged" majority[32]. This could stratify society in ways that undermine meritocratic ideals and social cohesion.

Regulatory gaps already reflect this divide. In the United States, medical devices like deep brain stimulators undergo rigorous Food and Drug Administration (FDA) approval, but consumer-grade "neuro-wellness" headsets operate in a regulatory grey zone. A 2025 study by the NeuroRights Foundation found that the "vast majority" of brain implant companies collect data with "few limits, vague policies, and reserve sweeping rights to share it," including potential sale to advertising firms and AI companies[33].

Ensuring equitable access must be a core design principle, not an afterthought. The contrast between rigorous oversight for medical devices and minimal regulation for consumer neurotechnology creates a two-tiered system where the most vulnerable, patients with neurological conditions, may be best protected, while healthy consumers seeking cognitive enhancement face unknown risks.

### Informed consent in compromised states

Obtaining meaningful consent for experimental BCIs from patients with advanced ALS or locked-in syndrome is ethically fraught[34]. How do we protect vulnerable populations from undue hope or coercion while facilitating access to potentially life-changing technology?

The paper Brain Pioneers and Moral Entanglement: An Argument for Post-trial Responsibilities in Neural-Device Trials highlights the ethical challenge of informed consent in compromised states. Because neural-device trials often involve patients with severe neurological conditions, their capacity to fully understand risks, long-term implications, and the experimental nature of BCIs may be impaired. This creates a moral entanglement: while participation offers hope for restored function, it also raises concerns about whether consent is truly autonomous. The authors argue that researchers and clinicians must adopt heightened ethical safeguards, ensuring that consent is not only formally obtained but substantively meaningful, with ongoing reassessment of patient comprehension and voluntariness. In this way, informed consent in compromised states becomes a dynamic responsibility, requiring vigilance to protect identity, autonomy, and dignity throughout and beyond the trial[35].

## *Regulatory gaps and the governance vacuum*

The regulatory landscape is fragmented and reactive. Medical devices like deep brain stimulators undergo

rigorous FDA approval, but consumer-grade "neuro-wellness" headsets operate in a regulatory grey zone. There is no agreed-upon framework for evaluating cognitive enhancement devices. Key questions remain unanswered: What are the long-term (decade-long) effects of chronic brain stimulation? How do we define and measure "enhancement" versus "therapy"? International collaboration is needed to establish safety standards, efficacy benchmarks, and post-market surveillance protocols for this globally developing technology.

## *Toward a responsible future*

The long-term impact of BCIs will be shaped by the choices we make today. We propose the following pathways for responsible advancement. The primary focus of research and investment should remain on restoring health and function for people with disabilities. Success in this domain builds essential knowledge, trust, and ethical capital. Interdisciplinary teams, encompassing neuroscientists, engineers, ethicists, philosophers, and end-users, must collaborate from the outset. Value-sensitive design should be mandatory. The future of BCIs is too important to be decided solely by technologists and corporations. We need inclusive public dialogues, citizen assemblies, and educational initiatives to build societal literacy and shape policy. Regulatory bodies must work with scientists to create agile, evidence-based frameworks that can evolve with the technology. Core principles including transparency, auditability, and human oversight must be legally enshrined. Prioritizing investment in high-resolution non-invasive technologies (e.g., advances in magnetoencephalography (MEG), and functional near-infrared spectroscopy (fNIRS)) could help mitigate key ethical risks. Furthermore, exploring BCIs for collaborative problem-solving (e.g., "brain net" applications) could steer the technology toward collective, rather than solely individualistic enhancement.

## Comparative synthesis of BCI pathways

The divergent development of invasive, semi-invasive, and non-invasive BCIs is defined by a fundamental "invasiveness paradox," where the quest for high-fidelity signal resolution is perpetually at odds with long-term biological stability. As illustrated in Table 3, invasive systems provide the superior bandwidth necessary for decoding complex higher-order cognitive processes such as "inner speech". However, this benefit is constrained by a "biocompatibility bottleneck". The chronic foreign body response to penetrating electrodes leads to glial scarring and electrochemical degradation, which causes signal quality to decay over time. For patients without life-threatening conditions, this limited functional lifespan significantly complicates the risk-benefit calculus, as the high initial performance may eventually require invasive replacement surgeries.

In contrast, semi-invasive systems such as the "BeiNao-1" offer a compelling technical "middle way" by placing electrodes epidurally on the surface of the skull, without direct contact with brain tissue. While this results in a lower signal-to-noise ratio compared to penetrating arrays, it drastically reduces the risks associated with

**Table 3: Comparative analysis of BCI modalities.**

| Feature | Invasive (e.g., Neuralink and NeuroXess) | Semi-invasive (e.g., BeiNao-1 and Stentrode) | Non-invasive (e.g., EEG, fNIRS, and MEG) |
|---|---|---|---|
| Placement | Intracortical (penetrates brain tissue) | Epidural/endovascular (on or near the brain surface) | Extracranial (on the scalp) |
| Signal quality | High: Superior bandwidth and single-neuron resolution | Medium: Better than EEG; avoids some tissue noise | Low: Susceptible to noise/artifacts; low spatial resolution |
| Long-term risks | High: Glial scarring, infection, and signal decay over time | Moderate: Reduced immune response; avoids direct tissue damage | Low: Negligible physical risk; primary risks are psychological/data-related |
| Clinical benefit | High-dexterity motor control; complex speech decoding | Functional rehabilitation (e.g., robotic arm control) | Wellness, basic gaming, and diagnostic monitoring |
| Policy complexity | Highest: Requires rigorous FDA/ National Medical Products Administration (NMPA) clinical trial oversight | High: Clear medical pathway but requires new safety standards | Medium: Often falls into "consumer grey zones" with limited data protection |

immune response and neuronal death. This approach facilitates a "quasi-practical" interface that may offer superior long-term stability for motor and speech rehabilitation. Meanwhile, non-invasive BCIs represent the most scalable modality, avoiding surgical risks entirely. However, they suffer from a "bandwidth chasm," where the attenuation of signals by the skull limits their precision to basic commands, making them highly effective for general wellness but insufficient for complex motor restoration.

These technical distinctions carry profound implications for the global "governance vacuum". From a policy perspective, the high cost and surgical requirements of invasive technologies risk creating a "neuro-social divide," where a "neuro-enhanced" elite gains cognitive advantages over an "unplugged" majority. Conversely, consumer-grade non-invasive devices often operate in a regulatory grey zone where sensitive neural data may not be protected by medical-grade privacy standards like GDPR. To ensure equitable societal access and protect "neuronal integrity," the authors argue that future policy must be stratified: prioritizing rigorous clinical oversight for medical implants while subsidizing high-resolution non-invasive technologies to prevent a new axis of social inequality.

## Conclusion

BCIs force us to confront the deepest questions about what it means to be human in a technologically mediated age. The allure of transcending biological limitations is potent, but the risks of alienation, inequality, and unintended harm are equally real. This analysis underscores that the most significant obstacles are not on the circuit board, but in our legal institutions, ethical imagination, and social contracts.

The goal must not be unfettered acceleration, but meaningful integration. A successful BCI future is one where technology strengthens, rather than undermines, human dignity, autonomy, and shared prosperity. Achieving this requires a deliberate shift from a purely techno-optimistic narrative to a holistic, stewardship-oriented model. By foregrounding ethics, equity, and long-term societal impact, we can guide the development of BCIs toward a future that truly enhances the human condition, rather than one that inadvertently compromises it. The interface we build with our own brains will ultimately reflect the values we choose to encode within it.

## Author contributions

ZDZ and RE reviewed the literature and drafted the manuscript. YCW and EKT provided critical comments, and revised and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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## Data availability statement

No new datasets were generated or analyzed in this review. All referenced materials are derived from previously published peer-reviewed literature, clinical trial registries, and publicly accessible policy documents.

## Ethics statement

Not applicable.

## AI statement

The AI tool was not used for data analysis, data generation, image processing, or scientific content creation.

All outputs were carefully reviewed and verified by the authors, who take full responsibility for the final content.

## Conflicts of interest

The authors declare no conflicts of interest.

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