Editorial

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Brain-computer interfaces: A lifeline for paralysis or a Pandora's box for humanity?

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SUMMARY: Recent advances in computerized technologies, neuroscience, and materials and engineering have transformed brain-computer interfaces (BCIs) from conventional unidirectional signal recording systems (brain-to-device) to bidirectional closed-loop neuromodulation systems (brain-device-brain). BCI-based devices enable direct information exchange between the human central nervous system and external electronic devices, and they are widely used in scenarios such as rehabilitation of patients with dyskinesia or enhancement of the self-care ability of disabled individuals. This editorial discusses the rapidly evolving field of BCIs, highlighting both their transformative potential to restore neurological function and the emerging ethical concerns associated with neural data access, cognitive enhancement, and human autonomy. The academic consensus and future translational prospects are also discussed. This article attempts to provide insightful, balanced, and critical viewpoints to help BCI-related research. Indeed, the future of BCIs will depend not only on technological innovation but also on society's ability to establish robust ethical and regulatory frameworks. Whether BCIs become a lifeline for millions of patients or a source of new societal risks will be determined by the choices made today.

Keywords: brain-computer interface, neural decoding, rehabilitation, ethical problems, paralysis

1. Introduction

As computerized technologies are increasingly used in clinical practice, the topic of brain-computer interfaces (BCIs) has garnered attention. Advances in neuroscience (such as neural signal acquisition, surgical implantation technology, and neuromodulation technology), computerized technologies (such as decoding algorithms and artificial intelligence (AI)), and material and engineering (such as implantable system design, microsensors, and organically compatible materials) have facilitated the development of and research on devices based on BCIs. Earlier BCI-related research mainly focused on unidirectional brain-to-device control, whereas post-2024 studies highlight bidirectional brain-device-brain interactions and functional restoration for patients with severe neurological conditions or sequelae. This study attempts to, from critical viewpoints, briefly summarize insights and concerns regarding the clinical applications of BCI-based devices based on rapidly updated evidence. We hope to encourage readers to think about the actual value of BCIs.

2. Updating definitions and technical classification of BCI-based devices

The definition of a BCI is changing as technology advances. According to the Brain-Computer Interface Society (*1*) and a study by Jain *et al*. (*2*), there are several components of the newest definition of a BCI: *i*) A BCI is bidirectional, namely, brain-device-brain. The core upgrade of modern BCIs is closed-loop bidirectional interactions rather than conventional one-way signal acquisition. It is fundamentally different from neural prostheses that rely on direct peripheral nerve conduction, such as cochlear and retinal implants. It also differs from electromyography-based control devices that require voluntary muscle contractions. *ii*) The interactions are real-time or nearly real-time. *iii*) It is useful at improving neurological function and has translational value. We should bear in mind that the definitions are constantly updated as technology and applications advance. For example, interactions between the brain and external electronic devices are currently being studied. As devices are developed in response to clinical requirements, many third-party devices may achieve better modulation, neural activity, and neurological functions. Thus, "bidirectional" might be changed to "multidirectional", involving multiple devices, which may form a complex BCI-based system to improve clinical outcomes for patients.

Currently available BCIs can be roughly classified into three categories according to invasiveness and clinical practicability: *i*) An invasive BCI: Devices of this type require conventional surgical implantation of intracortical electrode arrays with high signal bandwidth and decoding precision. These invasive devices are primarily used for restoration of high-level motor function. *ii*) A semi-invasive BCI: Devices of this type require minimally invasive surgical technology, such as intravascular electrode sensors or robots. A semi-invasive BCI balances biosafety and signal quality and is the most popular type in terms of clinical translation. *iii*) A noninvasive BCI: Devices of this type use technologies such as electroencephalography (EEG) or electromyogram (EMG)-based wearable systems and do not require surgery. A typical device of this type is the postmarketing Hybrid Assistive Limb (HAL) system in Japan, which has a noticeable efficacy in improving walking function in patients with stroke (*3*) and spinal cord injury (*4*). One appeal of these systems is the absence of surgical risk. Moreover, some devices even achieve the so-called "idiodynamics" of simple body actions, such as leg lifting or leg extension, which can only be seen in science fiction, and significantly improve walking function. However, these devices have limitations. For HAL, the lack of evidence from large-scale, multicenter, and long-term randomized controlled trials might be a problem (*3*). The long-term efficacy of this treatment is unknown. In addition, the high cost may further restrict its application.

3. Applications of BCI-based devices

BCI-based devices have been widely used for the restoration of motor function and communication in patients with various neurological diseases, such as stroke and spinal cord injury, Alzheimer's disease (AD), Parkinson's disease (PD), and psychiatric disorders such as attention deficit hyperactivity disorder (*2*). Between 2024-2026, the numerous studies that directly implanted BCI-related devices is breath-taking. One noticeable aspect is their use to improve speech. Wairagkar *et al*. implanted 256 microelectrodes into the ventral precentral gyrus of a patient with amyotrophic lateral sclerosis-related dysarthria. This BCI-based device can synthesize a voice with closed-loop audio feedback by decoding neural activity; using this device, the patient was able to talk in real-time and sing a short song (*5*). Thus, BCI-based device can help to enable patients with dysarthria to regain the ability to speak. Qian *et al.* reported a BCI-based 256-channel-microelectrocorticographic speech decoding device for Mandarin Chinese. They made remarkable improvements in Mandarin Chinese-based tonally integrated direct syllable neural decoding, which might be useful for patients with aphasia (*6*). In addition to speech, Vargas-Irwin *et al*. observed the single-unit ensemble activity recorded in two patients with a cervical spinal cord injury in whom two 96-channel intracortical microelectrodes were implanted in the precentral gyrus. They found that single-unit ensemble activity recorded in a single precentral gyrus has the potential to generate more related signals, which might be used in BCI-based rehabilitation to produce gestures (*7*). Willsey *et al*. developed a finger-based BCI device that was able to control three independent fingers in two dimensions (*8*). This device made significant improvements in the finger functioning of patients with a severe spinal cord injury. Dexterous finger control can be achieved, allowing patients with tetraplegia to control devices such as robotic limbs and ultimately perform daily self-care (*8*). This device has great value in improving welfare, a sense of enablement, recreation and social connectedness, and quality of life (QOL) in patients with paralysis. Recent studies are clinical explorations with small sample sizes. Although they obtained primary evidence indicating that BCI-based devices have the potential to restore communication and motor control in individuals with severe paralysis, subsequent well-designed clinical studies are highly anticipated.

In this regard, BCIs seem to represent a lifeline for patients with diseases that are traditionally regarded as "incurable" diseases and "hopeless" dysfunctions and to light a candle to reignite their hope of performing self-care.

In addition to rehabilitation of patients, BCI-based devices are also useful in scientific research and even improve the daily lives of healthy participants. In terms of research, BCI can serve as a valuable tool for investigating the neural mechanisms underlying human cognition, decision-making, and language processing. Non-invasive EEG-based BCIs can be used in research on real-time attention quantification and attention/memory training in educational research. In terms of the daily lives of healthy users, non-invasive BCI-based devices may be used for sleep regulation and detection of mental fatigue. Thought-activated smart home operation, immersive VR/AR interaction, and wearable neural feedback systems based on BCI technology can be developed to improve the QOL of both patients and healthy users. Accordingly, BCI may be involved in many settings of daily life in the future.

4. Discussion of current BCIs and their advantages, technical bottlenecks and ethical risks

Advantages: To date, a BCI is the only technical approach that enables clinicians to bypass damaged somatic pathways and directly restore central neural output, significantly improving the QOL and social participation of disabled populations. Personalized and precise neuromodulation is superior to conventional pharmacology and physical therapy. Moreover, "thought activation" is achieved for some simple but important motors, which means that paralyzed patients can fully or partially perform self-care using BCI-based robots, which have great economic and social value. The global BCI market reached USD 2 billion in 2024 and is projected to grow to USD 3.25 billion by 2029, showing strong translational and commercial potential.

Technical Bottlenecks: Currently, the known invasive BCI-related concerns include unavoidable surgical risks, immune rejection, limited electrode lifespan, and long-term signal instability. Non-invasive BCIs are commonly restricted by low signal-to-noise ratios, poor anti-interference performance, and marked individual differences in terms of decoding accuracy.

Ethical risks during clinical application: Because BCI technology is still emerging, many indispensable data for their clinical use are still insufficient, such as long-term safety and efficacy data on invasive implants. In the ethical domain, bidirectional BCIs may bring unprecedented challenges (*9*), such as neural privacy leakage risks, cognitive stratification caused by cognitive enhancement technologies, potential manipulation of human free will *via* targeted brain stimulation, and risks of misuse in military, criminal, and mandatory neural intervention scenarios. These risks should be fully considered in future BCI research. Moreover, the current heatedly discussed concerns, such as neuro-rights, cognitive liberty, mental integrity, psychological continuity, highlight the importance of ethical concerns in BCI research.

Regulatory challenges: Although governments worldwide have established relatively powerful regulatory systems for the development of medicine and medical devices, the regulatory system for BCI still faces challenges due to its emerging and fast-developing nature. Technological iteration usually occurs and areas of technical interest easily change; this is particularly true for AI-related computerized technologies. These contexts may cause difficulties in establishing a stable, balanced, and operable BCI-related regulatory system. This is an important issue that should be addressed by global health administration authorities worldwide.

The nature of consciousness is an unaddressed topic: To date, the precise decoding of abstract cognition and complex emotional signals has yet to be achieved (*10*). This issue cannot be resolved before the question of "what is the nature of consciousness" has an appropriate scientific answer. Metaphysical neuroscience research relies on elements that can be "observed", "captured", or "recorded", such as neurotransmitters and electroneurographic signals. One can easily understand the dilemmas in the development of consciousness-related BCIs, which also lie at the heart of the development of neuro-medications: PD-related medications (mainly for motor dysfunction) are sufficient and effective, whereas AD-related medications (mainly for cognitive impairment) are insufficient and have relatively poorer efficacy, which might be due to insufficient knowledge regarding the "nature of consciousness". Accordingly, BCIs have made progress in motor decoding and sensory restoration, but efforts such as decoding higher-order cognition, subjective experiences, and consciousness remain a major scientific challenge. Current neuroscientific frameworks have not yet provided a comprehensive understanding of consciousness, limiting the development of cognition-oriented BCI systems. Revolutionary breakthroughs need to be made in neuroscience, not only in observational approaches but also in research mindsets, so that the essence of consciousness can be further recognized. BCIs may play a role as a powerful tool for that research.

5. Current academic consensus and future prospects

In light of the latest available literature, we have summarized the current academic consensus on BCI research and applications based on the current technical level and related ethical concerns:

i) Current BCI-related research should prioritize meeting the stringent demands of disabled patients, such as functional restoration and medical rehabilitation, rather than development and research for non-essential demands, and especially applications for non-medical aims, such as enhancements in motor or cognitive functions in a healthy person (making a "superhuman"). Exaggerated "mind-reading" narratives should be rejected.

ii) Invasive high-precision systems and non-invasive safe, wearable systems should be developed in parallel. Semi-invasive BCIs, and minimally invasive ones in particular, are predicted to be the optimal clinical solution in the next 5–10 years.

iii) Advances in AI-driven decoding algorithms and flexible bioelectronic materials may lead to significant breakthroughs in BCI-related devices.

iv) The establishment of the aforementioned BCI-related ethical principles is an urgent task for researchers worldwide. Underlying topics should include, but not be limited to, repair priority, cautious enhancement, and strict supervision, restricting non-medical elective cognitive enhancement, and protecting neural autonomy and mental privacy. Standardized neural data privacy protection systems will be constructed synchronously.

6. Conclusions

Undoubtedly, BCIs have entered a new era of closed-loop neuromodulation and clinical translation, as they gradually begin to play a crucial role in scenarios such as rehabilitation of patients with dyskinesia or enhancement of the self-care ability of disabled individuals. BCIs are regarded as the most transformative neurotechnologies and they have great commercial value. Nevertheless, technical stability, long-term clinical safety and

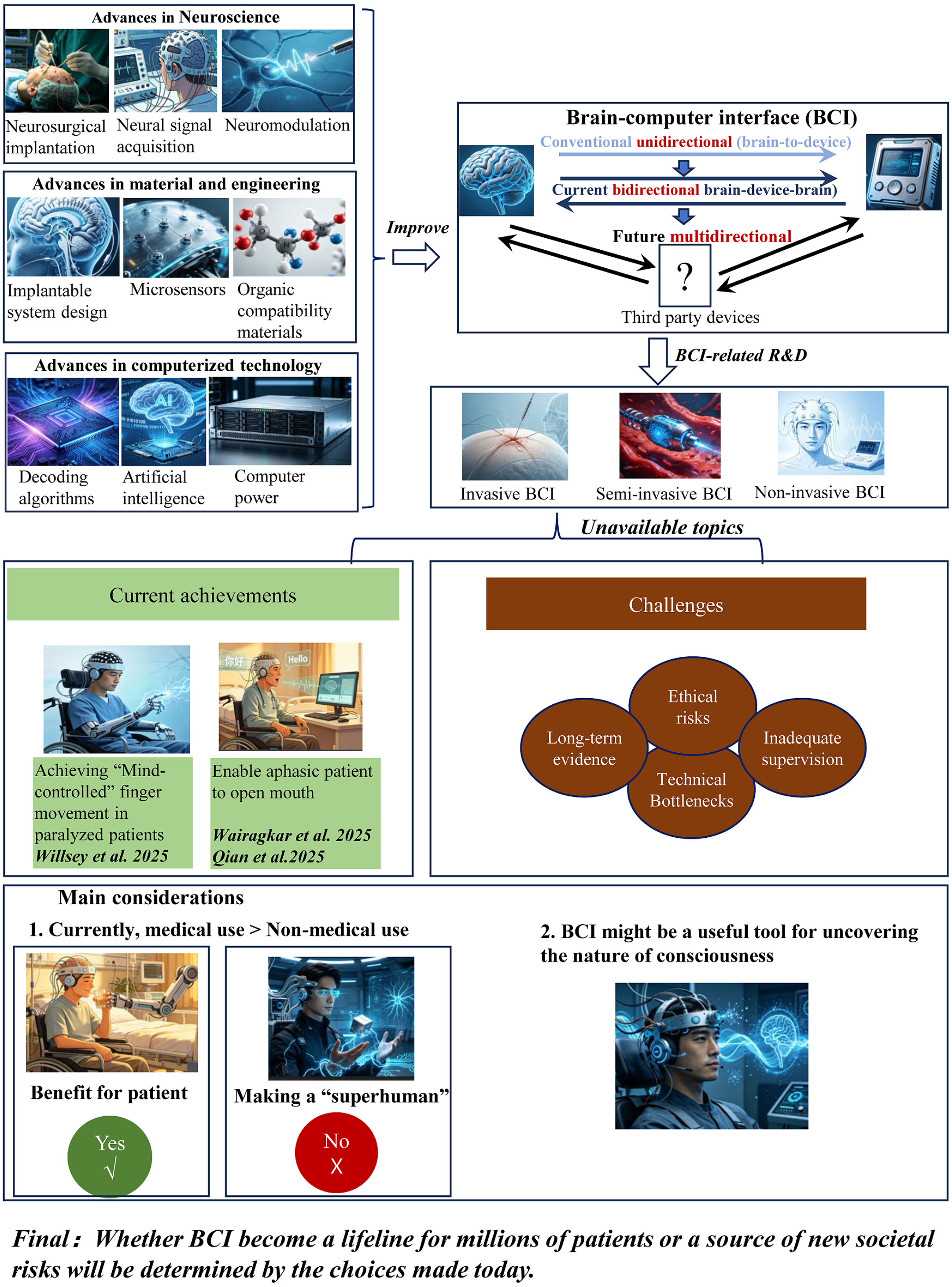

Figure 1. Brain-computer interfaces: A lifeline or a Pandora's box for humanity?

efficacy, and ethical risks are limiting the maturity of the field. The future of BCIs will depend not only on technological innovation but also on society's ability to establish robust ethical and regulatory frameworks. Whether BCIs become a lifeline for millions of patients or a source of new societal risks will be determined by the choices made today (Figure 1).

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References

1. Brain-Computer Interface (BCI) Society. BCI definition. *https://bcisociety.org/bci-definition/* (accessd May 28 2026).
2. Jain A, Raveendran S, Nair KPS, Ramakrishnan S. Brain-

computer interface: An update for the clinicians. Front Hum Neurosci. 2026; 20:1777024.

3. Yuzhu L, Krishnaswamy G. Robotic-Assisted rehabilitation in stroke patients using the hybrid assistive limb (Hal): A narrative review. Technol Health Care. 2026;9287329261440743.
4. Koda M, Kubota S, Kadone H, Miura K, Funayama T, Takahashi H, Yamazaki M. Robotic rehabilitation therapy using Hybrid Assistive Limb (HAL) for patients with spinal cord lesions: a narrative review. N Am Spine Soc J. 2023; 14:100209.
5. Wairagkar M, Card NS, Singer-Clark T, Hou X, Iacobacci C, Miller LM, Hochberg LR, Brandman DM, Stavisky SD. An instantaneous voice-synthesis neuroprosthesis. Nature. 2025; 644:145-152.
6. Qian Y, Liu C, Yu P, *et al*. Real-time decoding of full-spectrum Chinese using brain-computer interface. Sci Adv. 2025; 11:eadz9968.
7. Vargas-Irwin CE, Hosman T, Gusman JT, Pun TK, Simeral JD, Singer-Clark T, Kapitonava A, Nicolas C, Shah NP, Avansino DT, Kamdar F, Williams ZM, Henderson JM, Hochberg LR. Gesture encoding in human left precentral gyrus neuronal ensembles. Commun Biol. 2025; 8:1315.
8. Willsey MS, Shah NP, Avansino DT, Hahn NV, Jamiolkowski RM, Kamdar FB, Hochberg LR, Willett FR, Henderson JM. A high-performance brain-computer interface for finger decoding and quadcopter game control in an individual with paralysis. Nat Med. 2025; 31:96-104.
9. Gordon EC, Seth AK. Ethical considerations for the use of brain-computer interfaces for cognitive enhancement. PLoS Biol. 2024; 22:e3002899.
10. Chen X, Fu Z, Zhang P, Chen X, Huang J. Intracortical brain-machine interfaces with high-performance neural decoding through efficient transfer meta-learning. IEEE Trans Biomed Eng. 2026; 73:518-529.

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