Review

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The application of brain–computer interfaces in spinal cord injury rehabilitation

Progress and prospects

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Abstract

Spinal cord injury (SCI) is a severe neurological disorder that often results in long-term motor and sensory dysfunction, leaving patients highly dependent on external care, while current rehabilitation approaches remain limited in their efficacy. In recent years, brain–computer interfaces (BCIs), as a multidisciplinary frontier technology, have demonstrated unique advantages in SCI rehabilitation. By bypassing the damaged spinal pathways and establishing a direct communication channel between the brain and external devices, BCIs enable motor recovery, sensory restoration, and induction of neuroplasticity, while also showing potential in alleviating chronic neuropathic pain and improving psychological well-being. A growing body of experimental and clinical studies has confirmed that BCIs can restore partial motor control and tactile perception, thereby enhancing rehabilitation efficiency and improving patients' quality of life. However, their clinical translation remains constrained by challenges such as signal stability, long-term electrode safety, adaptive decoding algorithms, and ethical concerns. With the continuous development of artificial intelligence, novel biomaterials, and immersive technologies such as virtual reality, BCIs are expected to evolve toward more personalized, home-based, and intelligent rehabilitation solutions, accelerating their clinical application and offering new therapeutic hope for SCI patients.

Abbreviations: AI = artificial intelligence, AR = augmented reality, BCI = brain–computer interface, BSI = brain–spine interface, ECoG = electrocorticography, EEG = electroencephalography, FES = functional electrical stimulation, fMRI = functional magnetic resonance imaging, fNIRS = functional near-infrared spectroscopy, ICMS = intracortical microstimulation, LFP = local field potential, MEG = magnetoencephalography, MRI = magnetic resonance imaging, MUA = multi-unit activity, NIRS = near-infrared spectroscopy, SCI = spinal cord injury, STIMO = stimulation movement overground, SUA = single-unit activity, TENS = transcutaneous electrical nerve stimulation, tSCS = transcutaneous spinal cord stimulation, VR = virtual reality, WISCI II = walking index for spinal cord injury II.

Keywords: brain–computer interface, functional electrical stimulation, motor recovery, neurorehabilitation, sensory restoration, spinal cord injury, virtual reality

1. Introduction

Spinal cord injury (SCI) is a severe neurological condition often caused by external forces such as traffic accidents, falls, or violent trauma.[1] Patients typically exhibit varying degrees of motor, sensory, and even autonomic nervous system dysfunction below the level of the injury. In severe cases, patients may be permanently paralyzed and bedridden, resulting in a significant decline in quality of life and imposing a heavy burden on families and society.[1] Statistics show that the global incidence and disability rates of SCI remain high, and currently, there are no effective treatment methods that can completely cure paralysis.[2] Traditional rehabilitation methods such as acupuncture, massage, physical therapy, electrical stimulation, and exercise training can improve function to some extent but are limited by their efficacy, significant individual variability, and lack of long-term maintenance.[3]

With the rapid integration of neuroscience and engineering, brain–computer interfaces (BCIs) have emerged as a

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new focal point in SCI rehabilitation research. BCIs establish a direct information channel between the brain and external devices, bypassing the damaged spinal cord conduction pathways, and enabling the reutilization of motor intentions and sensory feedback.[4] They not only offer the possibility of restoring motor and sensory functions for patients but also demonstrate potential in alleviating chronic pain and improving psychological well-being. In recent years, an increasing number of studies and clinical trials have validated the application value of BCI in SCI rehabilitation. This paper will systematically review the application progress, existing challenges, and future development directions of BCI in SCI rehabilitation based on a comprehensive review of the existing research.

2. Technical foundations of BCIs

2.1. Classification of BCIs

Based on the method of signal acquisition, BCI is primarily divided into two major categories: invasive and noninvasive (Fig. 1). Invasive BCI involves surgically implanting electrodes into the cortex or deeper neural structures, such as electrocorticography (ECoG), local field potentials, single-unit activity, and multiunit activity (MUA).[5] Their advantages include high signal quality, good spatial resolution, and temporal accuracy, enabling complex and stable control. However, they come with risks such as surgical complications, infection, and electrode degradation.[6,7] Noninvasive BCI records brain signals through methods such as electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS), functional magnetic resonance imaging (fMRI), and magnetoencephalography (MEG) on the scalp surface.[8] Their advantages include safety, noninvasiveness, and scalability, but they are limited by noise interference and insufficient signal resolution.[6,7]

Additionally, BCIs can be categorized into unidirectional and bidirectional based on interaction mode: the former only enables signal transmission from the brain to the device, while the latter incorporates a feedback loop to achieve bidirectional communication between the brain and the device.[9] In recent years, bidirectional BCIs have gained prominence because they can simultaneously facilitate motor output and sensory input, forming a closed-loop regulation system that more closely mimics the natural functioning of the nervous system.[10–12]

2.2. How BCIs work

BCI systems typically consist of four components: signal acquisition, signal processing, feature extraction and decoding, and peripheral control (Fig. 1).[13] The electrical signals generated by the brain are collected via electrodes and then undergo filtering, noise reduction, and feature extraction to eliminate artifacts and irrelevant information.[14] Subsequently, a computer uses algorithms to classify and decode the signals, identifying motor or sensory intentions, and drives external devices such as robotic arms, prosthetics, exoskeletons, or functional electrical stimulation (FES) systems.[15,16] With advancements in deep learning and pattern recognition, the accuracy and real-time performance of signal decoding have continuously improved, making the clinical application of BCI increasingly feasible.[17,18]

2.3. Evolution of BCIs

The development of BCIs can be traced back to the early 20th century. In 1924, German psychiatrist Hans Berger[19] first recorded and described the EEG of humans, marking the first time that human brain electrical activity could be objectively observed and laying the foundation for subsequent BCI research. Over the following decades, scientists gradually recognized that EEG signals could reflect the functional state of the brain. However, the idea of connecting these signals to external devices was

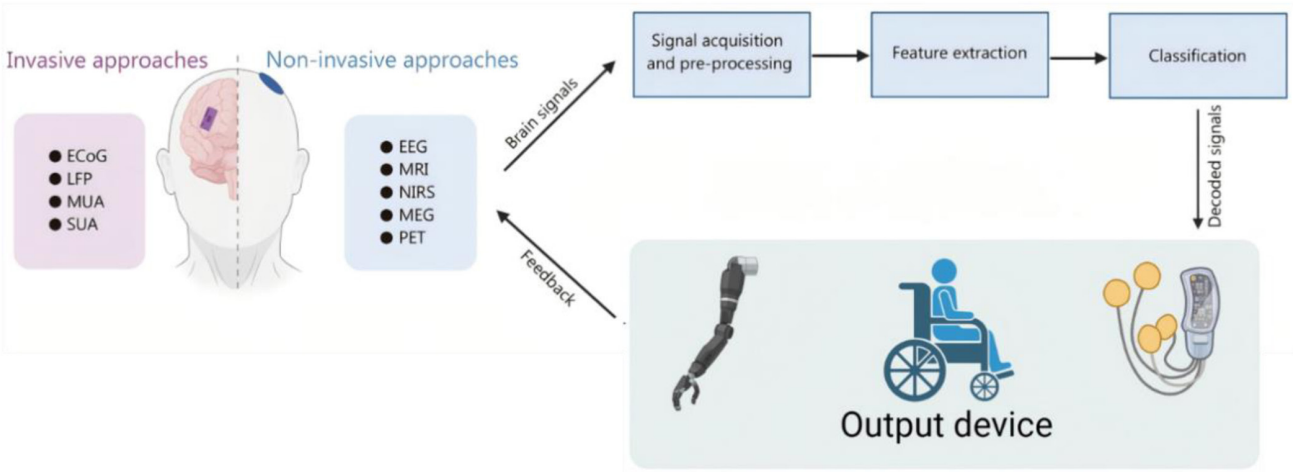


Figure 1. The classification of BCIs and how BCIs work. ECoG = electrocorticography, EEG = electroencephalography, LFP = local field potentials, MEG = magnetoencephalography, MRI = magnetic resonance imaging, MUA = multiunit activity, NIRS = near-infrared spectroscopy, PET = positron emission tomography, SUA = single-unit activity.

not formally proposed until 1973.[20]That year, American scholar Vidal[21] first introduced the concept of "BCI" in his paper, marking the beginning of BCI as an independent research field.[22]

The 1980s and 1990s were the exploratory phases of BCI.[23] Researchers primarily relied on noninvasive EEG to attempt to control computer cursors or simple external devices using brain rhythms. Experiments during this phase were mostly laboratory-based, limited by signal processing and computational capabilities, resulting in limited practical applications.[24] However, they demonstrated the possibility of "controlling devices with thoughts." Meanwhile, with advancements in single-cell recording and cortical EEG (ECoG) technology, invasive BCI began to emerge, enabling the acquisition of higher-resolution signals and laying the technical foundation for subsequent animal experiments and clinical exploration.[25]

In the 21st century,[26] BCI research entered a period of rapid development. On one hand, significant improvements in computer processing power and signal analysis algorithms have made real-time signal decoding possible[27]; on the other hand, demands from rehabilitation medicine and neuroscience have driven BCI toward clinical applications. In the early 2000s,[7] BCI based on motor imagery began pilot testing in stroke and SCI rehabilitation, enabling patients to control virtual environments or simple mechanical devices via EEG to perform grasping and movement tasks. Research during this period not only focused on "whether control is possible" but also emphasized integration with rehabilitation training to explore potential promotional effects on neural plasticity.[28–30]

After 2010,[31] BCI entered a new phase of clinical trials and multimodal fusion. Notable achievements include invasive electrodes enabling precise grasping and feeding movements with robotic arms for quadriplegic patients[15]; noninvasive BCI combined with FES or exoskeletons to enable walking training for SCI patients.[32] Additionally, the concept of closed-loop BCI has emerged, where while the brain sends motor signals to control the device, the device also provides real-time sensory feedback to the brain, achieving bidirectional interaction akin to "human-machine integration." For example, Flesher et al.[33] used intracortical microstimulation (ICMS) to transmit tactile feedback from the robotic arm to the patient, enabling them to perceive tactile sensations from the "hand," significantly improving operational efficiency and naturalness.

In recent years, BCI research has expanded further, moving beyond single-purpose motor control to broader domains such as sensory restoration, language decoding, emotion recognition, and even pain management.[34] Meanwhile, the introduction of artificial intelligence and deep learning has greatly improved the efficiency and accuracy of signal decoding, enabling BCI to better address individual differences and environmental noise.[35] Researchers have also proposed the "I^3 model" (interface–interaction–intelligence), dividing BCI development into three stages[36]: the initial interface, which establishes the connection between the brain and the device; followed by interaction, emphasizing two-way feedback between humans and devices; and finally, intelligence, where BCI systems possess adaptive learning and highly personalized capabilities. This model not only reflects the trajectory of technological evolution but also reveals the direction of future development.

Overall, BCI development has progressed from conceptualization and experimental exploration to clinical application, gradually transitioning from laboratory-based scientific fantasy to practical rehabilitation.[37,38] Despite ongoing challenges such as signal quality, stability, and ethical considerations, its evolutionary trajectory clearly indicates that BCI is continuously advancing toward higher precision, bidirectional functionality, and intelligence, and is poised to become one of the core technologies in neurorehabilitation medicine in the future.[38,39]

3. Application of BCI in SCI rehabilitation

Currently, the value of BCI in SCI rehabilitation is mainly reflected in the restoration of motor function, reconstruction of sensory function, promotion of neural plasticity, and regulation of pain and psychological state. Importantly, BCI should be understood primarily as an enabling interface for neural signal acquisition and translation, rather than as the sole therapeutic driver of these outcomes. In most current paradigms, the observed benefits are more likely to result from the combined effects of training, feedback, stimulation, and other rehabilitation components supported by the BCI framework. This distinction is particularly relevant in pain and psychological regulation, where attentional engagement, expectation, and immersive environments may also contribute to the reported effects. The following will elaborate on this with specific research examples.

3.1. Restoration of motor function

Motor dysfunction is the most obvious and severe issue for SCI patients.[40] BCI decodes the electrical activity of the motor cortex, converting the patient's "motor intent" into commands for external devices, thereby bypassing the damaged spinal cord pathways.[1,3,16] In the stimulation movement overground (STIMO) clinical trial conducted by Lorach et al.,[32] the integration of BCI with overground stimulation training enabled some SCI patients to regain continuous and stable walking ability, including walking over complex terrain, thereby overcoming the previous limitation that rehabilitation training was largely confined to flat surfaces (Fig. 2A, B). In addition to locomotor recovery, several studies have enabled patients to directly control robotic arms through BCIs to perform grasping actions. For example, Hochberg et al.[41] reported in the BrainGate trial that two quadriplegic patients used implanted BCIs to control robotic arms for three-dimensional grasping, including performing daily activities such as drinking coffee (Fig. 2C). Brunner et al.[42] further showed that combining motor imagery with visual feedback and FES could



Figure 2. The application of BCI in SCI rehabilitation (Sections 3.1–3.3). (A, B). In the STIMO clinical trial, combining BCI with spinal cord stimulation enables some SCI patients to regain continuous and stable walking ability, even navigating complex terrains.[32] (C) This shows scenes where patients control robotic arms via BCIs (Reprinted with pemission from reference[41], copyright 2012, Nature.) (D). The effects of brain–computer interface training with motor imagery and FES for patients with severe upper limb paresis after stroke.[42] (E) A hand rehabilitation system where tactile sensors are integrated into a robotic arm, as in Flesher et al.'s research,[33] with signals transmitted back to the sensorimotor cortex, allowing patients to perceive object contact.[33] (F) BCI with transcutaneous electrical nerve stimulation (TENS) and VR, using EEG and skin conductance to detect pain signals and provide real-time intervention, significantly reduces patients' pain perception[43] (G). In the tactile feedback system reported by Flesher et al.,[33] artificial sensory feedback not only restored contact perception but also significantly reduced the time required for grasping and placing objects. BCI = brain–computer interface, EEG = electroencephalography, SC = spinal cord, TENS = transcutaneous electrical nerve stimulation, VR = virtual reality.

help paralyzed patients regain partial limb motor function, with patients demonstrating greater improvements than those receiving traditional rehabilitation after long-term training (Fig. 2D). Together, these findings demonstrate the effectiveness and clinical potential of BCI in motor rehabilitation and activities of daily living. Relevant reviews also indicate that these technologies allow patients to control prostheses or robotic arms via brain signals for self-care operations, highlighting the significant value of integrating BCI with robotic technology in future rehabilitation.[44]

3.2. Reconstruction of sensory function

Without sensory feedback, motor function recovery is often inefficient, and movements are stiff.[45] Bidirectional BCI achieves artificial sensation by installing sensors on external devices to feedback tactile or pressure signals to

the brain. Flesher et al.[33] incorporated tactile sensors into a robotic arm and transmitted the sensory signals back to the motor-sensory cortex, allowing patients to perceive object contact through artificial tactile feedback (Fig. 2E). O'Doherty et al.[46] used ICMS feedback in monkey experiments, enabling monkeys to distinguish objects of different textures, demonstrating the feasibility of artificial tactile feedback. Nicolelis et al.[47] further applied this method to SCI patients. Compared with traditional rehabilitation, the artificial tactile feedback group had significantly higher tactile scores, indicating the advantages of BCI in sensory recovery.[47] However, achieving sensory function recovery requires extremely high precision in signal acquisition and long-term stability of electrodes, which remains one of the technical challenges.

3.3. Regulation of pain and psychological state

Chronic neuropathic pain is a common and difficult-to-treat complication in SCI patients, characterized by sensations such as burning or electric shocks, often accompanied by psychological anxiety and depression.[48] BCI has also been explored in this field. Aurucci et al.[43] combined BCI with transcutaneous electrical nerve stimulation and virtual reality, using EEG and skin conductance to detect pain signals and provide real-time intervention, significantly reducing patients' pain perception (Fig. 2F). Additionally, some studies have found that patients who have undergone BCI implantation or use exhibit improvements in cognition, mood, sleep, and quality of life, which may be closely related to the partial recovery of motor and sensory functions.[49] This suggests that BCI has the potential to become a multifunctional tool in comprehensive rehabilitation, not only restoring physical functions but also improving patients' overall health status.

It is worth noting that, in addition to sensory perception and pain modulation, artificial tactile feedback can also improve the efficiency of motor tasks and activities of daily living. Flesher et al.[33] showed that tactile feedback from a sensorized robotic arm not only enabled patients to perceive object contact but also significantly reduced the time required to grasp and place objects, from 20.9 to 10.2 s (Fig. 2G). These findings further indicate that bidirectional BCI may enhance sensorimotor integration by transforming artificial sensory signals into more precise and efficient motor control.

3.4. Promoting neural remodeling

Recent studies indicate that BCI can significantly stimulate neural plasticity mechanisms. In animal models, synchronous stimulation of the brain and spinal cord can remodel central neural circuits beneath the motor cortex and enhance motor performance.[50] Clinically, the "DiSCIoser" program utilizes BCI-assisted motor imagery training to promote upper limb functional recovery in the subacute phase of SCI patients[51]; Athanasiou et al.[52] proposed a multimodal training protocol integrating motor imagery, action observation, augmented reality, and wearable devices. Long-term follow-up confirmed this approach enhances cortical activity and promotes sensorimotor circuit remodeling, providing crucial clinical evidence for SCI rehabilitation.[52] Concurrently, brain–spinal cord interfaces applied in natural gait recovery demonstrate how such "digital bridges" facilitate functional reorganization of residual neural pathways (Fig. 3).[32] Further studies employ noninvasive brain–spinal interface with transcutaneous spinal cord stimulation (tSCS) closed-loop feedback systems to achieve real-time motor intention driving and enhanced cortical plasticity.[53] Additionally, stroke patients undergoing BCI intervention exhibit more pronounced structural and functional lateralization reorganization, providing direct evidence for neural plasticity.[54]

4. Challenges and future prospects for clinical translation

Despite continuous breakthroughs in the application of BCIs in SCI rehabilitation, their clinical translation still faces numerous challenges. First, there are technical limitations: noninvasive BCIs are prone to signal degradation from noise interference, resulting in insufficient decoding accuracy,[6] while invasive methods, though capable of providing high-precision signals, carry risks such as infection, immune reactions, and long-term degradation of implanted electrodes.[25,55] Second, there are significant individual differences among patients. Patients with different injury locations, severities, and disease durations exhibit varying responses to BCI. Additionally, the current lack of large-scale, long-term clinical trials limits the accumulation of efficacy evidence and clinical adoption.[29] Furthermore, as BCI can decode and even partially "read" brain signals, ethical issues related to patient privacy and freedom of thought have become increasingly prominent.[38,56] Without comprehensive laws, regulations, and regulatory mechanisms, this may lead to social concerns and resistance. More realistically, BCI devices are generally expensive, lack portability and stability, and are still far from being used in daily clinical practice and home rehabilitation. In summary, the core challenges that BCI must address to achieve widespread clinical translation include enhancing signal stability, reducing implantation risks, enabling personalized applications, and accumulating high-quality clinical evidence—all while ensuring safety and privacy protection.

In the future, the development of BCIs in SCI rehabilitation will increasingly focus on personalization, intelligence, and clinical accessibility. With the deep integration of artificial intelligence and big data, BCI's signal decoding capabilities and adaptability will continue to improve, enabling it to develop personalized rehabilitation plans based on individual patient differences and optimize the training process in real time.[57,58] Additionally, the application of new materials and minimally invasive implantation technologies will enhance the flexibility and biocompatibility of electrodes, reducing the risk of immune rejection and long-term degradation, thereby improving system safety and stability.[22,55] BCI will also integrate with emerging

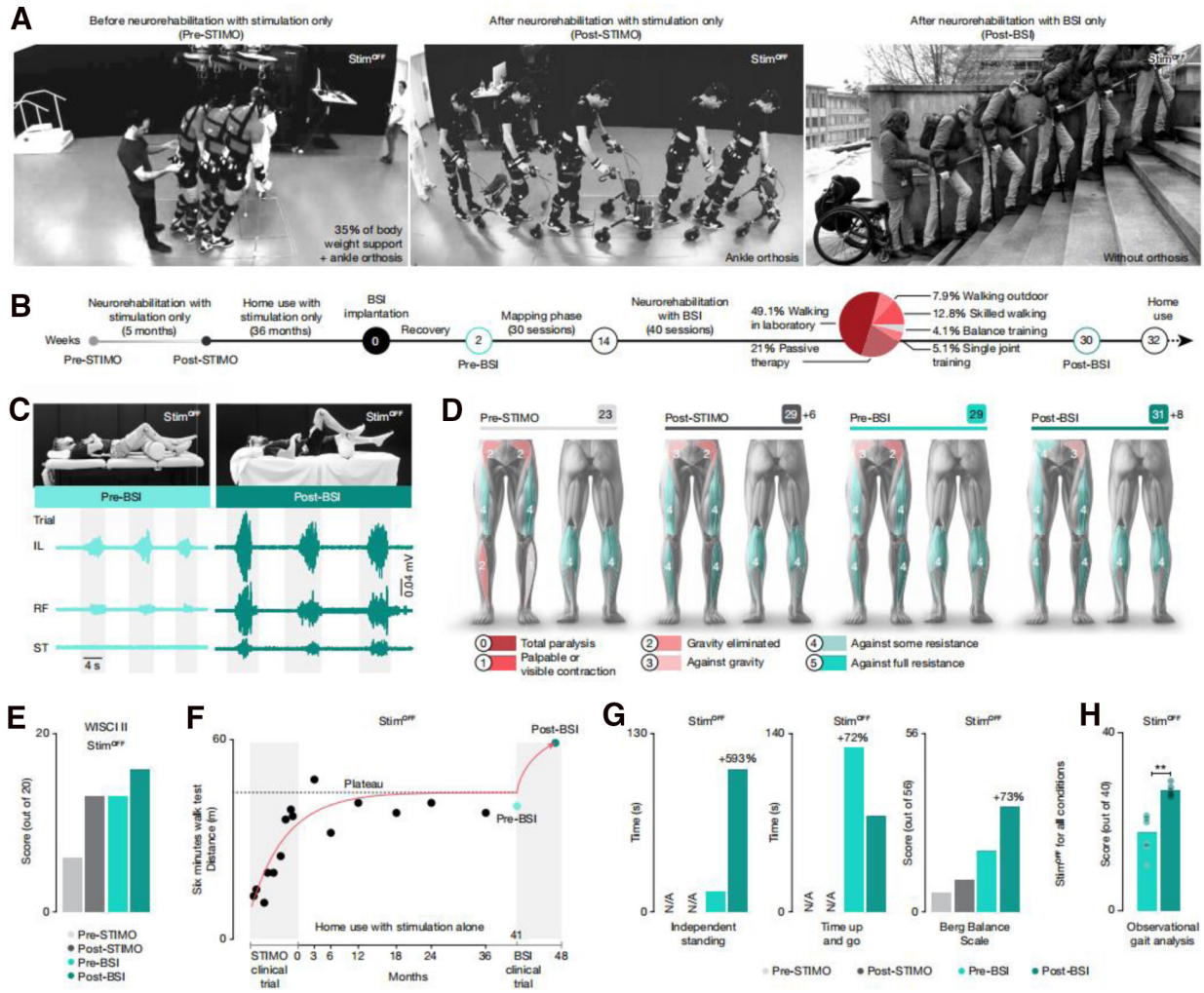


Figure 3. The application of BCI in SCI rehabilitation (Section 3.4).[32] (A) Chronophotography illustrating the walking ability of the participant without any stimulation before enrolling in the STIMO clinical trial (pre-STIMO), after its completion (post-STIMO), and after completion of the STIMO-BSI clinical trial (post-BSI). (B) Timeline of the two clinical trials, including a pie chart reporting the time during which the various types of neurorehabilitation exercises were practiced, as well as the home use of the BSI. (C) Photographs showing the maximal hip flexion and associated flexor muscle activity before and after neurorehabilitation. (D) Changes in lower limb motor scores over the course of both clinical trials. (E) Plots reporting improvements in WISCI II scores over the course of both clinical trials. Neurorehabilitation supported by the BSI restored the capacity to walk over 10 m with crutches without any assistance or stimulation. (F–H) Plots reporting quantifications of the 6 min walk test (F), weight-bearing capacity, time up and go, Berg Balance Scale (G), and observational gait analysis (H) (each dot refers to scores from a physiotherapist (n = 6, paired one-tailed t-test; $^{**}p$ = 0.002)). BCI = brain–computer interface, BSI = brain–spinal interface, N/A = not available, SCI = spinal cord injury, STIMO = stimulation movement overground, WISCI II = walking index for spinal cord injury II.

technologies such as virtual reality, augmented reality, and wearable devices to create immersive and engaging rehabilitation platforms, enhancing patient engagement and compliance.[59] As interdisciplinary collaboration deepens and clinical evidence continues to accumulate, BCI is expected to gradually move out of the laboratory and into hospitals and homes, becoming a key driving force for transformation in the field of neural rehabilitation.

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Ethical statement

Not applicable.

Conflicts of interest

Huajiang Chen serves as Associate Editor-in-Chief, Chen Xu serves as Editorial Board Members of this journal. They were not involved in the editorial review or decision-making process for this manuscript. All editorial decisions were made independently by other members of the Editorial Board who have no conflicts of interest.

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Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Author contributions

HC, BH—participated in research design and critical revision of the article.
XZ, KC, JM, BW—participated in the writing of the article.
CX, HC—reviewed the manuscript.

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