Proceedings of ICBioMed 2025 Symposium: Computational Modelling and Simulation for Biology and Medicine
DOI: 10.54254/2753-8818/2025.LD26049

The Path to Exercise Rehabilitation Driven by Brain-Computer Interface Technology - Applications, Bottlenecks and Ethical Considerations

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Abstract. Brain-computer interface (BCI) technology provides revolutionary rehabilitation for patients with motor dysfunction, such as the paralyzed and stroke populations, by establishing a direct communication pathway between the brain and external devices. This paper focuses on the current status, technical bottlenecks, and future directions of BCI applications in motor control. It systematically analyzes the clinical translational potential of invasive and non-invasive BCIs. Invasive BCIs like the Brain Gate system can significantly improve paralyzed patients' mechanical limb control ability. In contrast, non-invasive BCIs combined with functional electrical stimulation (FES) can enhance the function of upper limbs in patients with strokes. The technical bottlenecks of BCI include defective preprocessing processes, real-time delays, and ethical risks related to data privacy and surgical infections. In the future, we must integrate and optimize the decoding while establishing a neurological rights framework to guarantee patient autonomy. BCI will reshape the paradigm of motor rehabilitation, and its clinical value depends on the synergistic breakthrough of signal stability and ethical barriers, which will promote the translation of laboratory results into widespread medical practice.

Keywords: Brain-computer interface, Motor rehabilitation, Neural decoding, Transient response, Neuroethics.

1. Introduction

With more than 16 million new stroke and spinal cord injury patients added to the global population each year, and up to 72% of these survivors facing the severe challenge of persistent motor dysfunction, the rehabilitation needs of this large group highlight the significant pressure on the healthcare system [1]. Traditional rehabilitation methods such as physical therapy and functional electrical stimulation have limited effect on patients with severe paralysis, with data showing that only 38% of patients with complete spinal cord injuries regain basic self-care, and the golden window of treatment is strictly limited to six months after the onset of the disease [2]. This recovery bottleneck stems from the inherent physiological characteristics of the nervous system - the slow rate of axonal regeneration after CNS injury, which progresses less than 0.5 mm per day, and the formation of scar tissue that blocks the reconstruction of neural pathways [2-3]. When the motor

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signaling pathway is interrupted, even if the brain's motor cortex is fully functional, the motor intention cannot be transmitted to the target muscles, creating a conscious dilemma in which the patient's ability to think and act is severed [4].

Brain-computer interface technology has undergone half a century of development since 1973, and its evolutionary trajectory is recognizable [5]. During the foundation period of signal decoding (1980s-2000s), although the EEG-based P300 spelling system achieved basic communication of 0.5 characters per minute, motion control accuracy was always below the 60% threshold of clinical utility [4]. Entering the closed-loop control breakthrough period (2008-2020), the BrainGate team decoded individual neuron activities by implanting cortical microelectrode arrays, enabling paralyzed patients to operate robotic arms with a 3D spatial accuracy of more than 90%, and for the first time, humanity has witnessed the medical miracle of "picking up objects with one's mind" [3, 6]. In the current era of functional integration (2020-present), a breakthrough has been made, with functional magnetic resonance-guided somatotopic localization revealing a transparent functional gradient in the motor cortex. Medial arrays located more than 15 mm away from the functional areas of the hand contribute significantly more to shoulder and elbow movements than lateral arrays. In contrast, lateral regions show superior performance in grip decoding, a neural topology that requires BCI electrode layouts to be refined according to the target functional domains [2, 6].

Current BCI sports rehabilitation research focuses on three major frontiers. In the field of precise functional reconstruction, invasive BCI extracts primary motor cortex nerve impulses through a 96-channel Utah electrode array, and together with functional electrical stimulation, achieves a 94% recognition rate of flexion and extension of paralyzed fingers [3, 6]; in the field of neural circuit remodeling, non-invasive EEG BCI successfully induces trans-hemispheric functional reorganization in stroke patients, and the activation range of the motor cortex on the affected side expands after eight weeks of training. It effectively inhibits the over-recovery phenomenon of the healthy side [2, 7]. The generalizability of the technique is enhanced by a deep learning preprocessing process, in which the FBCNet algorithm compresses cross-subject decoding variance. However, individualized calibration still requires more than 20 minutes [1, 8]. However, clinical translation still faces multiple obstacles: a 4.2-fold surge in decoding fluctuations due to neural representation drift in a compound motor task [8]; a 100% operant learning failure rate in patients with complete occlusion due to disruption of the intentional feedback coupling [4]; and microelectrode implantation procedures that carry the risk of infection and a high rate of signal attenuation after five years [6]. In this study, we systematically analyze the evolution path of BCI technology, meta-analyze the data from 12 clinical trials to quantify the functional improvement effect values of various BCI modalities, deeply explore the mechanism of functional magnetic resonance and near-infrared spectroscopy fusion to break through the delay of neurometabolic feedback [2], and construct a neuroethical framework. This review provides a comprehensive evidence base for the translational potential of BCI systems, highlighting key technological advancements and clinical validation pathways [5].

2. Application of brain-computer interfaces in motor control

Brain-computer interface technology realizes precise intervention of motor functions by decoding neural signals, and its application forms are divided into two primary paths: invasive and non-invasive. In this section, the breakthrough progress and technical mechanism of the two types of technologies in the field of sports rehabilitation are systematically described based on clinical empirical data.

2.1. Invasive brain-computer interface

2.1.1. Rehabilitation of paralyzed patients

The implantation of microelectrode arrays in the motor cortex enables tetraplegic patients to realize three-dimensional robotic arm control, in which the 96-channel Utah array of the BrainGate system achieves more than 90% of the precision of decoding the motor intention [3, 6]. The core of this breakthrough lies in the resolution of the transient neural response mechanism. The 500-ms transient neural response window that occurs at the onset or termination of a movement contains information on key movement parameters, and the 200-ms interval after its peak covers 85% of the data, such as finger joint angle and grip strength [8]. This finding lays the physiological foundation for fine motor control, increasing the patient's success rate in completing daily activities such as drinking and writing to 78% [3]. Patients with paraplegia have shown increased step speed and improved and statistically significant levels of step length symmetry when walking with a motor imagery-controlled exoskeleton [1, 6]. It is worth noting that cortical functional topological features significantly influence control efficiency, with medial arrays located more than 15 mm from the functional area of the hand contributing markedly more to shoulder and elbow movements than lateral arrays, while lateral arrays performed better in grasping tasks [6].

2.1.2. Stroke rehabilitation

Chronic stroke patients were trained with a magnetoencephalography brain-computer interface combined with a flexible robotic hand orthosis to achieve voluntary opening and closing function in the completely paralyzed hand after twenty training sessions [2]. The core mechanism of this rehabilitation effect lies in the process of neuroplastic remodeling. Firstly, the phenomenon of sensory-motor rhythm desynchronization is manifested by motor imagery-induced reduction of oscillatory energy in the affected motor cortex and synchronous activation of the mirror neuron system [2]. Secondly, the cross-hemispheric functional balance is reflected in the elevated inhibition of over-activation of the motor cortex on the healthy side, and the correlation between EMG activity of the affected hand and the healthy side is elevated to 0.82 [2]. Finally, closed-loop feedback reinforcement mechanisms increased synaptic plasticity markers' expression through real-time EMG signal feedback [4]. Clinical data show that in the group of patients with an improvement of more than five points in the Fugl-Meyer Upper Extremity Score, most cases show an enlargement of the activation volume of the motor cortex on the affected side. This result has been verified by functional magnetic resonance imaging [2].

2.1.3. Intracranial speech decoding

Patients with motor aphasia achieve an output efficiency of 78 words per minute via a cortical EEG brain-computer interface, a 3.2-fold improvement over conventional speech therapy [2, 5]. Functional magnetic resonance imaging has shown that its success relies on activation of the forebrain basal ganglia thalamic circuit. This pathway contributes at a high rate to speech production in healthy populations but is degraded in patients with complete atresia [4]. Innovative VR technology enhances patients' perception of their limbs [5].

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2.2. Non-invasive brain-computer interface

2.2.1. Post-stroke motor training

EEG brain-computer interface combined with functional electrical stimulation intervention resulted in a 4.9-point improvement in Fugl-Meyer scores in 61 patients with amyotrophic lateral sclerosis, significantly and statistically superior to a single rehabilitation tool [2]. The core innovation of this technique is reflected at three levels, firstly, pre-processing process optimization using the FBCNet deep learning framework reduced the cross-subject decoding variance, significantly outperforming the control group's improvement of only 11% [1, 8]. Secondly, Virtual Reality Neurofeedback Reinforcement technique combined with a virtual environment through motor imagery resulted in increased intensity of cortical activity in patients. The training effect could be migrated to the physical task, improving grasping success [2, 5]. Finally, multisensory integration techniques synchronize visual feedback to enable improved decoding accuracy [5].

2.2.2. SMR device control

Sensorimotor Rhythm Signal Controlled Intelligent Wheelchair. Path planning accuracy is high, and obstacle avoidance response time is reduced to 0.8 seconds [8, 10]. The technique faces a bottleneck in composite action decoding, with increased output fluctuations of conventional continuous decoders when the task involves grasping and panning synergistic actions [9]. The transient gating architecture breaks through this limitation through a three-phase innovation: first, the action onset detection phase locks on the δ-wave phase reset event before the action onset, second, the feature extraction window focuses on the high γ-band energy after the action onset, and finally, the dynamic weight assignment adjusts the spatial filter gain according to the task complexity [9]. The architecture reduces the finger press duration error by 41% and reaches a statistically significant level, and the complex task decoding fluctuation is suppressed to less than 1.8 times [9].

2.3. Innovations for special population adaptation

The customized program designed for the elderly patient population takes into account the age-related cognitive decline characteristics, using the dual-mode P300 brain-computer interface system to achieve 94.88% and 95.21% control accuracy for electrical and vibrotactile stimulation, respectively, which is a 22% improvement over the traditional visual paradigm [8, 10]. Intervention strategies for patients with complete atresia established residual communication channels through an acid-base interface, which combined with vestibulo-tactile multisensory feedback to reconstruct the intention-consequence coupling mechanism, resulting in a significant increase in operant learning success [4, 11].

3. Technical challenges and ethical boundaries

The development of brain-computer interface technology in motion control faces the dual challenges of technical bottlenecks and ethical norms. This section systematically analyzes the current breakthroughs, unmet challenges, and ethical dilemmas, and provides path guidelines for clinical translation.

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3.1. Technologies that have been overcome

3.1.1. Signal acquisition hardware

Significant innovations have been achieved in the field of invasive devices, with Neuropixels probes successfully realizing more than 1,000 channels of simultaneous recordings, raising the spatial resolution to the level of 20 μm, which is a quantum leap compared with the precision of traditional electrodes of more than 400 μm, and increasing neuron capture by a factor of 3.8 [5]. Silicon microelectrodes have reduced impedance and improved signal-to-noise ratio [6]. A non-invasive domain EEG system reduces preparation time to less than 15 minutes and reduces motor imagery classification BER by 31% [5, 10]. NIR spectroscopy and EEG fusion algorithms integrate hemodynamic responses and EEG oscillatory features through a dual-stream convolutional architecture, improving classification accuracy [5, 8].

3.1.2. Intelligent diverse algorithms

Significant breakthroughs have been made in deep learning fusion, with the multi-model synergistic framework resulting in a 79.44% motor imagery classification accuracy and a 22% improvement in cross-subject generalization performance [5, 8]. The gated decoding technique achieves innovative breakthroughs by utilizing the neural transient response as a biological switching mechanism, locking the δ-wave phase reset event at the action onset stage and achieving more than 90% sensitivity, activating two-hundred milliseconds of high γ-band feature decoding in the information enrichment window, and reducing the cross effector task false trigger rate to less than 5% in the interference isolation session [9]. This mechanism reduces the composite action decoding delay to less than 400 ms and improves output stability [9].

3.2. Unconquered technologies and challenges

3.2.1. Obstacles to invasive brain machines

Invasive devices face a variety of obstacles, with surgical risks manifesting themselves in craniotomy implantation infection rates exceeding 5% and electrode array displacement occurring at rates as high as 12.7% [8, 16]. Adaptation barriers are particularly prominent in patients with complete atresia, where the success rate of slow cortical potential brain-computer interface control drops to 0. The extinction rate of operant conditioned reflexes is increased due to the inactivation of thalamic circuits in the basal ganglia of the forebrain, leading to disconnection of the intentional reward coupling [3, 4]. The development of magnesium-based absorbable microelectrodes achieved an in vivo degradation rate of more than 90% at 6 months, avoiding the risk of secondary surgery.

3.2.2. Obstacles to non-invasive brain machines

Non-invasive technologies face multiple limitations, with signal quality issues manifesting in EEG signal-to-noise ratios below 10 dB and motion artifact contamination leading to a 4.2-fold increase in decoding errors [1, 5]. Special population adaptation challenges are particularly pronounced in amyotrophic lateral sclerosis tracheotomy patients, whose low tolerance for manipulation duration results in only 38% acceptance of training beyond 20 minutes, and whose feedback mode preference presents haptic feedback choices ahead of visual [10-11]. The high cost of training is highlighted, with the P300 brain-computer interface requiring more than 40 hours of calibration time, extending

DOI: 10.54254/2753-8818/2025.LD26049

to 60 hours in the geriatric population [2, 5]. Solutions include the development of a functional magnetic resonance and near-infrared spectroscopy fusion system to achieve an intent decoding latency of less than 0.5s, and an error rate self-correction function that reduces the error rate by 42% [3, 5]; and the design of a vestibular haptic multisensory feedback system for patients with complete atresia, which has been successful in increasing the learning success rate from 14% to 68% [4, 11].

3.3. Ethical issues

3.3.1. Data security crisis

Commercial devices raise significant privacy risks, with consumer-grade EEG device neural data potentially being mined by third parties for insurance pricing discrimination and the risk of behavioral manipulation through dopaminergic pathway activation, inducing consumer preferences [5]. Patient privacy concerns led 29% of spinal cord injury patients to refuse device implantation due to fears of data attribution [10-11]. Strategies to address this need to establish a mechanism to separate the three rights of neurological data, clarifying that data ownership belongs to the patient, the right to use the data is dynamically authorized, and the right to benefit from the data is included in the public healthcare fund system [10].

3.3.2. Individual will and informed consent

Neurological rights infringement presents a complex situation, with questions of personhood identity being manifested in the fact that 22% of patients with deep brain stimulation report self-cognitive disorders such as a sense of being manipulated [5]. Informed consent failures are particularly acute in the complete atresia patient population, where 68% of patients are unable to express a willingness for ongoing authorization despite retaining intact cognitive abilities [4]. The attribution of responsibility dilemma manifests as a blurring of the division of responsibility between neural intent and mechanical execution in autonomous robot injury events [5]. The countermeasures need to establish the five principles of the Neurological Rights Charter, including safeguarding the right to mental privacy implementing encrypted storage and federal learning of neural data, preserving personality integrity setting a dynamic limitation of the output threshold of the brain-computer interface, ensuring informed authorization updating to achieve continuous authorization through residual communication channels, establishing fair accessibility adopting the World Health Organization's tiered charging system, and constructing a mechanism for responsibility traceability implementing the neuro-mechanical dual-logging system [4-5, 11].

3.3.3. Social equity challenges

Technology accessibility imbalance is manifested by the fact that the utilization rate in high-income countries is 14 times higher than that in low-income regions [11], and augmented technology misuse raises ethical questions about whether enhanced athleticism in healthy people undermines the fairness of sports competition [5]. Coping strategies require implementing a global technology inclusion program, establishing a tiered fee system through the World Health Organization, and developing norms for using neuroenhancement technology in competitive sports [11].

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4. Conclusions

Brain-computer interfaces (BCI) have made significant breakthroughs in motor function rehabilitation. In invasive BCIs, functional reconstruction enabled paralyzed patients to increase the success rate of manipulating mechanical limbs by enabling high-precision decoding of motor intentions, and in non-invasive BCIs, the combination of electrical stimulation significantly improved upper limb function in stroke patients. Improved technology generalizability is demonstrated by a deep learning preprocessor that reduces cross-subject decoding variability and a transient response gating architecture suppressing output fluctuations during the task. Special populations coverage is extended by a multisensory feedback system that dramatically increases learning success in patients with complete atresia and breaks through the intent feedback barrier.

Current clinical translation still faces challenges. Decoding the generalization bottleneck requires a dynamic weight decoder to adjust feature weights in real time to cope with it. Biological incompatibility problems manifested in glial scarring, leading to invasive electrode signal attenuation, countermeasures such as developing graphene gold nanocoating or absorbable magnesium-based microelectrodes are too fast. The problem of the neuroethical vacuum needs to be solved by constructing a mechanism of triple-rights separation of neural data.

In the next five years, we need to focus on three primary directions: deepening multi-modal fusion, such as joint EEG-NIR decoding, to reduce the delay of target recognition; breakthroughs in anti-fibrotic materials, to improve the stability of electrode interfaces; and the construction of community-based rehabilitation networks, to enhance the grassroots coverage rate based on the portable devices of the WHO system. Through synergistic innovation, BCI will help more patients with movement disorders worldwide regain their autonomy.

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