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VR-MI-BCI for Spinal Cord Injury Rehabilitation: Limitations of Current Research and Design of an Improved Experimental Protocol

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Abstract. Paralysis caused by spinal cord injury can result in the loss of motor function in patients, and the combination of VR with motor imagery (MI) and brain-computer interface (BCI) technology shows considerable potential as a rehabilitation approach. This article first provides a brief introduction to the fundamental principles of this rehabilitation method, and then reviews the common problems that exist in current related research: many experiments lack appropriate control groups, the methods of motor imagery are not standardized, and the statistical methods used for data analysis also have limitations. These issues may compromise the reliability of the findings. To address these issues, this paper theoretically designs an improved experimental protocol, refines subject grouping, establishes a standardized motor imagery guidance procedure, incorporates multi-channel signal monitoring to remove interference signals, selects a linear mixed model for data analysis, and also includes long-term follow-up to observe rehabilitation outcomes. This article analyzes how this optimization plan can mitigate the biases present in previous studies, but also discusses the practical difficulties that will still be encountered during its implementation. This improved approach may provide a useful reference for future rehabilitation research.

Keywords: Spinal cord injury, Motor imagery brain-computer interface (MI-BCI), VR rehabilitation, Neural reconstruction

1. Introduction

Spinal cord injury (SCI) is a type of neurological injury that has a high likelihood of causing disability, often leading to paralysis of the lower body or severely restricted mobility. Paralysis not only substantially affects individuals' daily lives but also imposes a significant burden on families and society. According to the World Health Organization, in 2021, approximately 15.4 million people worldwide were living with spinal cord injuries. In recent years, with the development and integration of VR, MI, and BCI, groundbreaking progress has emerged in the treatment of SCI. This approach utilizes MI-BCI to decode motor intentions and employs VR to provide an immersive environment, thereby forming a system that facilitates neural rehabilitation and enhances motor

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function. However, with the proliferation of related studies, methodological issues in experimental design have become increasingly prominent. For example, control groups are often not clearly defined, motor imagery strategies are not standardized, and the selected statistical methods have inherent limitations. These issues significantly undermine the reliability of research findings and their clinical applicability. This paper will discuss classic cases and shortcomings in VR-MI-BCI rehabilitation research and offer targeted optimization strategies, aiming to provide a reference for the methodological standardization of future research in this field.

2. Principles of intervention in the treatment of SCI-induced paralysis

In order to understand why VR-MI-BCI can be used to treat SCI paralysis, it is necessary to first understand what SCI paralysis is. Spinal cord injury (SCI) has a high risk of causing disability because the spinal cord plays a crucial role in transmitting neural signals between the brain and the body. After an SCI, the brain cannot deliver instructions to the still-healthy muscle tissue, leading to paralysis of the patient. It is noteworthy that the muscle tissue and central nervous system of the brain in most patients remain unchanged compared to those of healthy individuals. In other words, when patients perform motor imagery (MI), their brains are still capable of producing normal RED or RES electroencephalographic signals. The role of MI-BCI is to serve as a functional bridge across disrupted neural pathways by decoding EEG signals associated with motor imagery and translating them into control commands for the VR environment. Ultimately, the outcomes of successful movements are fed back to the brain in a multimodal form through corresponding animations generated in VR, stimulating the brain to produce new neurons and ultimately achieving recovery and therapeutic effects.

Traditional approaches to SCI paralysis treatment primarily rely on high-repetition training. These conventional methods use continuous repetition of movements to help the muscles and nervous system regain strength and coordination. Nevertheless, traditional treatment protocols have inherent limitations. A recovery plateau refers to a stage in which initial improvements are observed, but the rate of recovery gradually slows or even stabilizes as rehabilitation progresses. During this stage, patients may lose motivation as exercises become repetitive and monotonous, leading to boredom, reduced engagement, and diminished training effectiveness. In addition, traditional approaches often focus primarily on physical recovery while giving insufficient attention to cognitive and motivational factors, including the influence of perceived training outcomes on patients' motivation and engagement.

In the current experiments, the combination of VR and BCI effectively addresses the systemic challenges of these traditional treatments.

Conventional rehabilitation training primarily depends on peripheral limb activities to indirectly affect the central nervous system, whereas VR-MI-BCI directly targets the sensorimotor pathways of the cerebral cortex. Patients with spinal cord injury (SCI) face a distinct neurophysiological disorder: cortical reorganization, altered excitability, and disruption of sensorimotor connections lead to the loss of learned motor representations. Following prolonged paralysis, patients may even show reduced anticipatory EEG α/β modulation associated with leg movements. Researchers explicitly pointed out that this result suggests VR-BCI training may promote neural plasticity, strengthening sensorimotor pathways and functional connections related to motor control and recovery [1].

Traditional rehabilitation often faces bottlenecks in the recovery of balance and walking functions. VR-MI-BCI demonstrates quantifiable advantages in these areas through task-oriented repetitive training.

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Walking Function: In the aforementioned RCT, the WISCI scores of the WANR group showed a significant improvement from the baseline level before training, reaching 9.75 ± 2.14 at 9 months, whereas the control group did not exhibit a comparable enhancement. Another study on lower-limb exoskeleton BCI also found that VR training shortened the time required to achieve effective BCI control without reducing BCI efficacy, and in some cases, even improved it [1, 2].

Balance Function: A systematic review and meta-analysis (8 studies, 142 patients with incomplete SCI) showed that VR/AR interventions produced a significant improvement in balance function with a large effect size (SMD = 1.21, 95% CI: 0.04–2.38, p = 0.046). VR, as an adjunct to conventional physical therapy, offers additional potential benefits [1].

Traditional rehabilitation primarily focuses on motor function, whereas the potential clinical benefits of VR-MI-BCI may extend to areas such as pain management and psychological well-being.

Neuropathic pain: A case study involving a patient with complete T4 SCI showed that after 10 sessions of multimodal BCI protocol training, the patient's pain levels decreased, and non-spastic lower limb movements appeared. The protocol maintained or reduced pain levels while improving self-reported quality of life. Other studies have explored VR-BMI-integrated systems for the neurorehabilitation of chronic pain, providing preliminary evidence of their feasibility for alleviating chronic pain symptoms [1].

Psychological autonomy and quality of life: Research shows that VR-MI-BCI training can provide SCI patients with a sense of psychological autonomy, a feeling that plays a crucial predictive role in quality of life. Another case study similarly indicates that continuous use of BCI protocols can enhance quality of life and reduce and stabilize pain levels [1].

The repetitive and clinical nature of traditional rehabilitation training can easily lead to a decline in motivation and insufficient engagement among patients during the long rehabilitation process. VR-MI-BCI systematically addresses this challenge through an immersive and gamified training environment.

Motivation and Compliance: VR integrates motor imagery tasks into task-oriented virtual scenarios (such as virtual walking or cycling), allowing patients to complete high-intensity, high-repetition training while "accomplishing tasks." Research indicates that VR can overcome the limitations of traditional mirror therapy, such as insufficient user attention and motivation, by providing controlled, interactive, and multimodal experiences that support cognitive and motor learning.

Training Efficiency: A study on lower-limb exoskeleton BCIs found that VR training shortened the training duration without reducing the effectiveness of the BCI, and in some cases even improved it. This suggests that VR not only enhances the training experience but may also facilitate neural learning by promoting attention and engagement.

Compared with traditional treatment programs, VR-MI-BCI therapy has progressed from solely improving motor rehabilitation to becoming a comprehensive rehabilitation system encompassing neural modulation, functional recovery, pain management, psychological benefits, and training efficiency, showing significant improvements in multiple aspects of therapeutic outcomes. Nevertheless, existing studies still have several methodological limitations, such as the lack of control group settings, the absence of standardization for motor imagery strategies, and limitations in statistical methods.

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3. Common methodological deficiencies in existing representative studies

Firstly, the absence of control groups: In the clinical experimental design of VR-MI-BCI, there are evident design issues. A systematic review used the Cochrane risk of bias assessment tool and the PEDro scale to evaluate the methodological quality of the included studies. The results indicated that most studies lacked adequate randomization and appropriate control groups, and the review ultimately explicitly stated that "studies with larger sample sizes and long-term follow-up are needed to determine the effect size of the intervention" [3]. Even in studies using an RCT design, the overt nature of VR interventions makes it impossible to blind both participants and intervention implementers — a meta-analysis including six RCTs (142 participants) assessed using the RoB 2 tool found that all RCTs were rated as high risk of bias in the participant and personnel blinding domains, a deficiency attributed to the inherent characteristics of VR interventions [4]. These deficiencies collectively result in generally low levels of evidence in VR-MI-BCI rehabilitation research, severely limiting the transition from "feasibility verification" to "effectiveness confirmation".

Secondly, the lack of standardization in motor imagery strategies: The absence of standardization in motor imagery strategies is a core bottleneck limiting the comparability and reproducibility of VR-MI-BCI research. At present, no widely accepted standards have been established regarding the VR technologies used, levels of immersion, or application protocols. One reason is that studies differ in their research objectives and clinical contexts, making it difficult to establish a unified standard. A meta-analysis indicated that VR interventions show significant differences in terms of "technology used, immersion level, and application plans," covering a wide range from non-immersive systems to immersive head-mounted displays [4]. The presence of these differences makes effective comparison between experiments impossible, and statistical or summarizing work difficult, if not unfeasible. Another important issue is the lack of transparency in EEG acquisition and signal-processing parameters. A technical audit of ten high-density MI-BCI computational workflows revealed the widespread existence of "parameter non-transparency": studies frequently omit key deterministic variables such as the filter order, window function constants, and the final dimension of feature vectors, and fail to report the exact number of features used for classification. This obscures potential overfitting risks and hinders the accurate assessment of system generalization capability [5]. Most importantly, many experiments do not test participants' motor imagery ability or perform grouping based on it, which makes experimental results particularly susceptible to individual differences in participants' abilities and leads to ineffective experimental designs that cannot effectively distinguish participants with poor motor imagery ability. In summary, establishing effective and unified experimental design standards in the VR-MI-BCI field is extremely important and necessary. This will allow research in the field to move beyond isolated efforts, enable effective comparison of experimental results, and facilitate cumulative research. A VR-MI-BCI confirmatory study explicitly acknowledged that "although the sample size was larger than in previous studies, the relatively small sample size may limit the statistical power to detect subtle effects" [4].

Third, limitations in statistical methods: methodological weaknesses in statistical analysis may contribute to the limited quality of evidence in VR-MI-BCI rehabilitation research. Small-scale experimental issues are particularly pronounced. A meta-analysis on incomplete SCI included only 142 participants in total, with an average sample size of fewer than 24 participants per study [6]. Regarding multiple comparisons, some studies did not apply corrections for multiplicity; researchers justified this by stating that, due to the small sample size and the exploratory nature of the pilot

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trials, "strict corrections might obscure meaningful effects." Although this approach may be understandable in exploratory research, it considerably increases the risk of false positives. Concerning the completeness of reporting statistical methods, a systematic review found that only 83.3% of studies described the method of random sequence generation, and only 50% implemented allocation concealment [6]. Taken together, small sample sizes, the lack of multiplicity corrections, and incomplete reporting may weaken the reliability and interpretability of study findings.

In summary, the three methodological issues described above are interrelated and may compound one another. Imperfect control group settings render the reference benchmarks for statistical tests unreliable; heterogeneity in motor imagery strategies exacerbates the non-comparability of small-sample studies; insufficient statistical power further hampers the reliable detection of already weak intervention effects. Collectively, these factors result in a key consequence: VR-MI-BCI rehabilitation research remains primarily focused on 'feasibility validation' and lacks practical reliability at the clinical level.

4. Discussion

This study addresses the flaws of existing experiments by proposing improvements in five aspects: participant grouping, training paradigms, signal monitoring, data analysis, and follow-up. For participant grouping, three control groups were established: the VR-MI-BCI intervention group, the motor imagery-only group, and the blank control group. Randomization was applied to reduce selection bias and compensate for the previous absence of control groups. In the training phase, a standardized motor imagery guidance protocol was implemented. Training duration, imagined movements, verbal cues, and VR scenarios were standardized, and each session followed a fixed procedure, resolving previous inconsistencies in motor imagery strategies and ensuring uniform training conditions for all participants. During signal acquisition, multichannel devices were used to record EEG signals while monitoring artifacts, including those caused by eye blinks and muscle activity, allowing contaminated segments to be identified and excluded and thereby improving the reliability of the EEG recordings. Data analysis utilized linear mixed models (LMMs), which can handle repeated measures and more effectively analyze changes in rehabilitation indicators across multiple tests, overcoming the limitations of traditional statistical methods. Finally, a long-term follow-up design was incorporated, tracking patients for several months post-intervention, periodically assessing motor function to observe whether rehabilitation outcomes are maintained over time rather than focusing solely on short-term effects. This approach optimizes the entire process from experimental design to statistical analysis, though practical challenges such as participant recruitment difficulties, high equipment costs, and substantial individual variations in EEG signals still remain in practice.

5. Conclusion

This paper focuses on rehabilitation training that combines VR with motor imagery (MI) and brain-computer interfaces (BCIs), reviewing the existing problems in such studies and proposing improvement strategies. Analysis of the existing literature reveals that past research had shortcomings in experimental grouping, standards for motor imagery operations, signal processing, and statistical methods, resulting in limited credibility of the findings. To address these weaknesses, we designed three groups of controlled experiments, a unified motor imagery guidance protocol, multi-channel signal interference removal, and analyzed repeated measurement data using linear mixed models, while also including long-term follow-up to observe rehabilitation outcomes.

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However, several practical challenges remain in implementing the proposed protocol, including difficulties in participant recruitment, high costs of EEG equipment, large inter-patient signal variability, and the high level of patient cooperation required during training, all of which may affect effectiveness during application. In the future, as BCI devices become more compact and affordable, rehabilitation approaches combining motor imagery and VR may become more accessible for clinical use. The improvement strategies proposed in this paper may provide a reference for future spinal cord injury rehabilitation research and support the development of more rigorous VR-MI-BCI rehabilitation studies.

References

[1] Mannan, M. M. N., Palipana, D. B., Mulholland, K. et al. Virtual reality mediated brain-computer interface training improves sensorimotor neuromodulation in unimpaired and post spinal cord injury individuals. *Scientific Reports, 16*, 6215. https://doi.org/10.1038/s41598-026-36431-3

[2] Zhao, G., Alho, E. J. L., Wei, P., et al. Training with a non-invasive brain-machine interface, combined with virtual reality and assisted robotic locomotion, induces significant motor recovery and partial reversal of widespread cortical atrophy in asia a paraplegics: A randomized, controlled, single-center trial. *medRxiv*. DOI: 10.64898/2025.11.28.25340891.

[3] De Miguel-Rubio, A., Gallego-Aguayo, I., De Miguel-Rubio, M. D., Arias-Avila, M., Lucena-Anton, D., & Alba-Rueda, A. Effectiveness of the combined use of a brain–machine interface system and virtual reality as a therapeutic approach in patients with spinal cord injury: A systematic review. *Healthcare, 11*(24), 3189. https://doi.org/10.3390/healthcare11243189

[4] Liscano, Y., Arias Coronel, F., & Martínez, D. Effects of virtual reality on motor function and balance in incomplete spinal cord injury: A systematic review and meta-analysis of controlled trials. *Brain Sciences, 15*(10), 1071. https://doi.org/10.3390/brainsci15101071

[5] Škola, F., & Liarokapis, F. (2018). Embodied VR environment facilitates motor imagery brain–computer interface training. *Computers & Graphics, 75*, 59-71.

[6] Esteves, D., Vagaja, K., Andrade, A., & Vourvopoulos, A. (2025). When embodiment matters most: A confirmatory study on VR priming in motor imagery brain-computer interfaces training. *Frontiers in Human Neuroscience, 19*, 1681538. https://doi.org/10.3389/fnhum.2025.1681538