Proceedings of the 3rd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/2025.26329

Techniques Based on the Principles of MI: Rehabilitation of Neurologically Induced Motor Limitations

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Abstract. Neurological disorders are now the leading cause of illnesses and disability worldwide. It causes immense suffering to affected individuals and families and deprives communities and economies of human capital. Motor imagery (MI) is a cognitive process that involves mentally simulating movement without actual physical execution. It has emerged as a promising rehabilitation technique for individuals with movement impairments caused by neurological disorders. This review evaluates the advantages and challenges of various MI-based techniques, including brain-computer interface (BCI), Exoskeleton and virtual reality (VR). All these methods offered innovative pathways for motor function restoration. The application of MI-based techniques in rehabilitating motor deficits are explored in this work. Additionally, this paper discusses the future development of MI-based technologies in motor rehabilitation, focusing on multidisciplinary collaboration, technical innovation in accuracy, and clinical applications. The results show that the integration among MI-based technologies holds promise for creating more effective and personalized rehabilitation protocols, ultimately improving patient outcomes in neurorehabilitation.

Keywords: Motor imagery (MI), Neurological disorders, Motor rehabilitation, Brain-computer interface (BCI), Virtual reality (VR), Exoskeleton, Neurorehabilitation

1. Introduction

Neurological disorders often result in significant movement limitations, disrupting a person's ability to live a daily life. These limitations always occur due to damage or dysfunction of the neural system, which affects the communication between the brain and muscles.

Motor Imagery(MI) concludes the mental simulation of movement without actual physical movement. The principle behind MI is that imagining a movement activates similar neural circuits in the brain as those during actual movement, particularly in the motor cortex. This activation can promote neuroplasticity, a crucial ability for recovery from neurological injuries [1].

Combining MI with other rehabilitation technologies can amplify its effects: MI+VR: VR simulates real-life scenarios in which patients practice imagined movements, making treatment more effective and accurate. MI+Exoskeletons: MI can guide the movements of exoskeletons, helping patients regain strength and coordination through assisted movement.

This review's objection is to evaluate the integration of Motor Imagery(MI) with other advanced technologies such as BCI, Exoskeletons, and VR. Based on the current literature and clinical studies, it concludes the benefits, limitations, and future directions of these technologies and explores the combinations of these integrative rehabilitation strategies.

2. Motor imagery brain-computer interface

2.1. Theoretical basis

Implementing motor imagery technology in rehabilitation involves several key steps: signal acquisition, signal processing, equipment control, and real-time feedback. First, the patient's brain signals, generated during imagined limb movements, are collected. These signals undergo preprocessing, feature extraction, and classification. The processed signals are then decoded to determine the patient's intended movements. Finally, these decoded intentions are converted into control commands to operate the target devices and provide real-time feedback. Through these steps, communication and control between the human brain and external devices are achieved [2]. Figure 1 shows a simplified framework for this process.

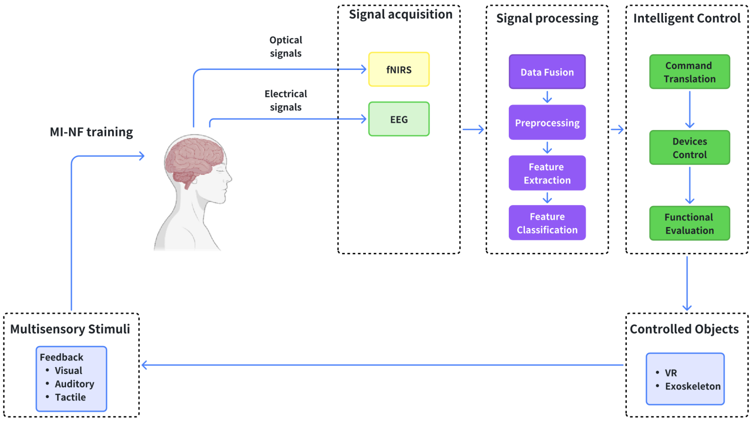

Figure 1. Motor imagery workflow

2.2. Evaluation

Studies have shown that MI systems offer certain advantages over traditional rehabilitation methods. Various research teams have integrated different algorithms into the signal-processing phase to improve the response time and accuracy of these systems. Table 1 compares the accuracy of motor imagery recognition across several studies that use different signal acquisition and processing methods.

Table 1. Accuracy comparison

Authors	Signal acquisition	Feature extraction	Classification	Accuracy(%)
Banghua Yang et al. [3]	EEG	CSP, FBCSP, 2Conv-FBCNet-cv	LDA, SVM	CSP: 51.3 ± 5.4 FBCSP: 48.8 ± 5.4 2Conv-FBCNet-cv: 59.4 ± 7.2
Miaomiao Guo et al. [4]	EEG, fNIRS	Relief-Mrmr	SVM	EEG + HbO: 86.93 ± 6.15 EEG + HbR: 87.13 ± 7.11 EEG + HbO + HbR: 88.33 ± 5.80
Yunfa Fu et al. [5]	fNIRS	signal mean and signal slope	SVM	72.25±0.004%

3. MI+ vitural reality(VR)

3.1. Theoretical basis and classification

As a visualization technology, VR blurs the boundary between the virtual world and the real world through multisensory feedback [6]. Applying VR technology to MI creates a virtual environment using VR technology to provide feedback and reduce external interference. Compared to traditional MI technology, it can provide a more immersive environment and enhance the fun and interactivity of the treatment process. This research searched for eight articles and selected six representative experiments from them. These six experiments only analyzed the motor imagination of simple upper limb movements such as finger grasping, arm flexion and extension, and wrist movements. They added many simple, lifelike virtual scene activities to them. By analyzing the different VR feedback systems in these six experiments, this work divided VR+MI into two categories: virtual reality technology that only uses visual feedback to assist MI and the other is virtual reality technology that provides multimodal feedback to assist MI. Classification will contribute to a better understanding of the different effects of VR on MI technology.

3.2. Methods

By observing Table 2, it can be seen that electroencephalography(EEG) has been widely used for collecting and comparing brain data before and after VR application and different levels of VR feedback at a higher time resolution [7], while electromyography(EMG) technology has been applied to evaluate participants' muscle tension during MI tasks, indirectly reflecting the difficulty of task execution. Photoplethysmography(PPG) is mainly used to monitor participants' heart rate changes and emotional reactions to evaluate the quality of user experience. Data analysis methods can be used to analyze the entire chart, and it can be found that single-modal VR technology can improve motor imagination. Multimodal VR technology performs better than single-modal VR technology in the recovery of damaged brain areas, functional reorganization, and accuracy of motor imagination detection. After integrating games, multimodal VR technology receives better feedback in terms of user experience than traditional single-modal VR technology. Multimodal VR technology has a high comfort level in treating neurologically induced motor limitations [8].

3.3. Evaluation

To evaluate the effectiveness of this technology, this work analyzed two typical examples of neural-induced motor deficits, one related to Parkinson's disease and the other related to stroke. The experiment focused on Parkinson's disease and mainly studied patients with static tremors, stiff gait, posture, delayed limb movements, standing up from a chair, and rapid alternating movements. This work discovered that these symptoms were significantly improved after applying VR+MI and demonstrated that VR+MI+routine physical exercise training is the most effective for elderly people with mild to moderate Parkinson's disease [9]. In terms of experimental treatment of stroke, the use of VR technology has a stronger degree of brain activation in stroke patients than in simple MI. For stroke patients who have no other rehabilitation options due to severe movement disorders, combining VR with MI is particularly beneficial [10]. Based on the analysis of all the experiments above, applying VR technology to motor imagery is beneficial for improving the therapeutic effect of motor imagery on neurological-induced motor defects. With the increased interest and modality, VR technology often provides patients with higher participation and rehabilitation efficacy. However, as the number of modalities increases, the increase in feedback may lead to information overload [11], causing mental fatigue in motor imagery tasks [12]. The cost of applying VR technology will also significantly increase, and VR technology also needs to consider whether patients will have adverse reactions such as resistance or dizziness to VR technology.

Table 2. A summary of experiments

VR classification						
	Modality	Authors	Dataset	material	Method	Results
Single modality(visual)	Visual	Jin Woo Choi et al. [6]	HP: 20 age: 20 to 37	EEG+VR	Comparison:IVR+MI; MD+MI	The ERD ratio of IVR-MI > MD-MI The accuracy of IVR-MI> MD-MI
		Kishor Lakshminarayanan et al. [7]	HP: 15(9 males, 6 females)	EEG+VR	Comparison: KMI+VR;KMI+NVA	ERD amplitude: VR-KMI>NVA-KMI Classification accuracy: VR-KMI>NVA-KMI
Multi-modalities	Visual +Auditory	Qiang Fang et al. [10]	16 patients	EEG+VR	Comparison:MI+VR; MI after VR;MI after voice;Voice。	Peak power spectral density in the alpha and beta frequency bands：MI+VR>MI after VR>MI after Voice>Voice
	Visual +Tactile +Olfactory	Reza Amini Gougeh et al. [13]	HP: 11(excluding those with cybersickness and scent sensitivity)	EMG+BCI+VR+PPG	Comparison: Motor imagery tasks; Motor priming tasks	Accuracy of motor imagery (MI) detection： Muti-modalities>single modalities
	Visual +Tactile+ Thermal+Auditory	Filip Škola et al. [14]	HP:19（median age was 26）	EEG+VR	Training task: using left and right hand MI to destroy asteroids in virtual space.	User Engagement： Gamified VR > traditional VR(External control, event based, using symbol guidance) The average optimal ERD value is -1.316 dB, with a standard deviation of 0.513.
		Carla Pais-Vieira et al. [8]	ASIA complete T4 spinal cord injury: 1;age: 52	EEG+VR	10 training sessions, twice a week, using this VR system	High levels of embodiment comfort reported. No significant adverse effects of VR were reported. Reduction in self-reported pain levels observed

[1] HP: healthy participants

4. Motor imagery-based brain-controlled exoskeleton

4.1. Overview of brain-controlled exoskeleton

Firstly, the EEG signal acquisition device will obtain the brain signal. Then, the EEG signal is processed through the processing and classification module, and finally, the signal is converted into control instructions to control the operation of external devices. Fig.2 shows the composition of the brain-controlled exoskeleton system. At the same time, the human body will also sense the movement of the exoskeleton to provide feedback to the brain [15]. At present, research on brain-controlled exoskeletons is still in the laboratory stage; how to acquire a large number of clean EEG signals and how to improve the generalization ability of brain-controlled devices for different patients still needs further research.

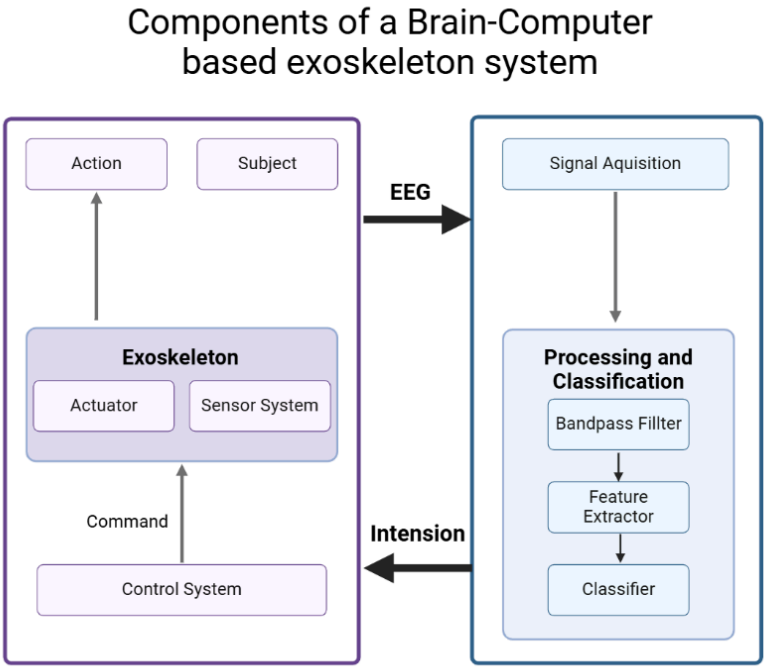

Figure 2. The composition of the brain-controlled exoskeleton system

4.2. Feasibility verification

A significant challenge for MI-BCI is the considerable variability in brain signal characteristics among individuals [16]. Additionally, stroke patients may experience damage to brain regions crucial for generating event-related desynchronization/synchronization (ERD/ERS), complicating the effectiveness of MI-BCI [17]. However, a previous study found that stroke patients with no prior experience with BCI were able to use MI-BCI as effectively as healthy individuals, with their performance not related to their degree of motor impairment. This finding led to the current investigation into the effectiveness of combining MI-BCI with the clinically validated robotic rehabilitation system.

4.3. Clinical study

According to Chen et al., MI-BCI for stroke upper limb rehabilitation is valid. Stroke patients were randomly assigned to either the control or BCI groups [18]. The BCI group received BCI treatment with exoskeleton feedback three times a week for four weeks. There were greater results for motor rehabilitation recovery in the BCI group than in the control group.

The study demonstrates that the soft robotic glove used in hand rehabilitation for stroke patients could be controlled by recognizing user intentions [19]. Thirty stroke patients were divided into three groups: robotic therapy, BCI-robotic therapy, or customary therapy. The BCI-robotic therapy group showed better hand function rehabilitation than the robotic therapy group.

The clinical effectiveness of a kind of buffet-friendly wrist exoskeleton has been shown [20]. Eleven healthy volunteers first imagined elbow movements, then underwent BCI training with the exoskeleton assisted by an exoskeleton for 30 minutes, and then imagined elbow movements again. The Motor-evoked potentials (MEPs) of the elbow movements were measured on two separate occasions. The results showed that MEPs increased after the training. A summarized description of the brain-controlled exoskeleton is shown in Table 3.

4.4. Limitations and prospects

The outlook of the follow-up work mainly includes the following points:

(1) Further optimize the structure of the exoskeleton. The current exoskeleton structure is not light enough and the movement action is simple, the subsequent consideration should be improved to be lighter and more flexible.

(2) For motor imagery, place and individual differences have a large impact on the accuracy, and better-adapted algorithms can be researched for the adaptive extraction of signal features.

(3) Although the current EEG signal pattern recognition scheme can meet the basic needs, the rate of classification and the asynchronous accuracy of the control system are insufficient. To improve the accuracy and speed of recognition, it is necessary to find more efficient algorithms and optimize the control system's software/hardware.

Table 3. A summarized description of a brain-controlled exoskeleton

Reference no.	Year	Targeted Regions	Types of Sensors Used	Advantages
Ref. [18]	2020	Upper limb	32 EEG channels	With exoskeleton guidance
Ref. [19]	2022	Hand	14 electrodes Emotiv EPOC	Soft, adaptable, and tailored
Ref. [20]	2020	Wrist	7 EEG channels	Cheap and light

5. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as follows: Motor imagery therapy has shown good performance in treating neurological-related motor defects. Integrating brain-computer interfaces, virtual reality, and exoskeleton technologies into motor imagery therapy can enhance clinical efficacy. Firstly, through BCI technology, patients' motor imagery can be transformed into control signals. Secondly, exoskeleton augmentation helps patients to engage in actual exercise, thereby achieving the goal of rehabilitation training. Moreover, virtual reality technology can provide patients with a safe, controllable, and fun environment, enhancing their immersion and training effectiveness. The study has shown that applying virtual reality and exoskeleton technology to brain-computer interfaces can be achieved [13], and personalized design needs to be considered in comprehensive design.

Acknowledgments

Qianyi Wang, Baining Zhang, Xinyu Xiao, and Wei Su contributed equally to this work and should be considered co-first authors.

References

[1] FitzGerald JJ, Lu Z, Jareonsettasin P and Antoniades CA. (2018) Quantifying Motor Impairment in Movement Disorders. Front. Neurosci, 12: 202.
[2] Curran E, Sykacek P, Stokes M, Roberts SJ, Penny W, Johnsrude I, Owen AM. (2004) Cognitive tasks for driving a brain-computer interfacing system: a pilot study. IEEE Trans Neural Syst Rehabil Eng, 12(1): 48-54.
[3] Banghua Yang, Jun Ma, Wenzheng Qiu, Yan Zhu, Xia Meng. (2022) A new 2-class unilateral upper limb motor imagery tasks for stroke rehabilitation training. Medicine in Novel Technology and Devices, Volume13, 2022, 100100.
[4] Miaomiao Guo, Leiguang Feng, Xiaogang Chen, Mengfan Li, Guizhi Xu. (2024) A novel strategy for differentiating motor imagination brain-computer interface tasks by fusing EEG and functional near-infrared spectroscopy signals. Biomedical Signal Processing and Control, 95: Part B, 106448.
[5] Fu, Y., Wang, F., Li, Y., Gong, A., Qian, Q., Su, L. & Zhao, L. (2022). Real-time recognition of different imagined actions on the same side of a single limb based on the fNIRS correlation coefficient. Biomedical Engineering / Biomedizinische Technik, 67(3): 173-183.
[6] Choi, Jin Woo, et al. (2020) Observing Actions Through Immersive Virtual Reality Enhances Motor Imagery Training. IEEE Transactions on Neural Systems and rehabilitation engineering. a publication of the IEEE Engineering in Medicine and Biology Society, 28(7): 1614-1622.
[7] Lakshminarayanan K, Shah R, Daulat SR, Moodley V, Yao Y and Madathil D. (2023) The effect of combining action observation in virtual reality with kinesthetic motor imagery on cortical activity. Front.Neurosci, 17: 1201865.
[8] Pais-Vieira C, Gaspar P, Matos D, Alves LP, da Cruz BM, Azevedo MJ, Gago M, Poleri T, Perrotta A and Pais-Vieira M. (2022) Embodiment Comfort Levels During Motor Imagery Training Combined With Immersive Virtual Reality in a Spinal Cord Injury Patient. Front. Hum. Neurosci, 16: 909112.
[9] Kashif, Muhammad et al. (2022) A Randomized Controlled Trial of Motor Imagery Combined with Virtual Reality Techniques in Patients with Parkinson's Disease. Journal of personalized medicine, 12(3): 450.
[10] Choy, Chi S et al. (2023) Virtual reality and motor imagery for early post-stroke rehabilitation. Biomedical engineering online, 22, (1): 66.
[11] Ma, S., Varley, M., Shark, L. K., and Richards, J. (2012) Overcoming the information overload problem in a multiform feedback-based virtual reality system for hand motion rehabilitation: healthy subject case study. Virtual Real, 16: 325–334.
[12] Talukdar, U., Hazarika, S. M., and Gan, J. Q. (2019) Motor imagery and mental fatigue: inter-relationship and EEG based estimation. J. Comput. Neurosci, 46: 55–76.
[13] Amini Gougeh R and Falk TH (2023) Enhancing motor imagery detection efficacy using multisensory virtual reality priming. Front. Neuroergon, 4: 1080200.
[14] Škola F, Tinková S and Liarokapis F (2019) Progressive Training for Motor Imagery Brain-Computer Interfaces Using Gamification and Virtual Reality Embodiment. Front. Hum. Neurosci, 13: 329.
[15] Gao X., Clarke R., Zhang D. (2022) A review on electroencephalography (EEG)-controlled upper limb exoskeletons towards stroke rehabilitation [J]. Brain Network and Modulation, 1(2): 80-87.
[16] Blankertz, B., Dornhege, G., Krauledat, M., Müller, K. R., & Curio, G. (2007) The non-invasive Berlin Brain-Computer Interface: fast acquisition of effective performance in untrained subjects. NeuroImage, 37(2): 539–550.
[17] Ang, K. K., Guan, C., Chua, K. S., Ang, B. T., Kuah, C. W., Wang, C., Phua, K. S., Chin, Z. Y., & Zhang, H. (2008). A clinical evaluation of non-invasive motor imagery-based brain-computer interface in stroke. Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference, 2008, 4178–4181.
[18] Chen, S., Cao, L., Shu, X., Wang, H., Ding, L., Wang, S. H., & Jia, J. (2020) Longitudinal Electroencephalography Analysis in Subacute Stroke Patients During Intervention of Brain-Computer Interface with Exoskeleton Feedback.

Frontiers in neuroscience, 14: 809.

[19] N. Guo, X. Wang, D. Duanmu, X. Huang, X. Li, Y. Fan, H. Li, Y. Liu, E.H. Yeung, M.K. To, J. Gu, F. Wan, Y. Hu. (2022) SSVEP-based brain computer interface controlled soft robotic glove for post-stroke hand function rehabilitation. IEEE Trans. Neural Syst. Rehabil. Eng, 30: 1737–1744.

[20] Jochumsen, M., Janjua, T. A. M., Arceo, J. C., Lauber, J., Buessinger, E. S., & Kæseler, R. L. (2021) Induction of Neural Plasticity Using a Low-Cost Open Source Brain-Computer Interface and a 3D-Printed Wrist Exoskeleton. Sensors (Basel, Switzerland), 21(2): 572.