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RESEARCH

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Impact of an upper limb motion-driven virtual rehabilitation system on residual motor function in patients with complete spinal cord injury: a pilot study

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Abstract

Background Assessing residual motor function in motor complete spinal cord injury (SCI) patients using surface electromyography (sEMG) is clinically important. Due to the prolonged loss of motor control and peripheral sensory input, patients may struggle to effectively activate residual motor function during sEMG assessments. The study proposes using virtual reality (VR) technology to enhance embodiment, motor imagery (MI), and memory, aiming to improve the activation of residual motor function and increase the sensitivity of sEMG assessments.

Methods By Recruiting a sample of 12 patients with AIS A/B and capturing surface electromyographic signals before, druing and after VR training,

Results Most patients showed significant electromyographic improvements in activation frequency and or 5-rank frequency during or after VR training. However, one patient with severe lower limb neuropathic pain did not exhibit volitional electromyographic activation, though their pain diminished during the VR training.

Conclusions VR can enhance the activation of patients' residual motor function by improving body awareness and MI, thereby increasing the sensitivity of sEMG assessments.

Keywords VR, Spinal cord injury, sEMG, Residual motor control ability

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Introduction

Aftermortem studies on clinically diagnosed complete spinal cord injury (SCI) consistently demonstrate the presence of neural tissue throughout the entire injury site [1–4]. Electrophysiological measurements further reveal that, even years after-injury, patients with complete SCI can continue to exhibit residual motor activation phenomena when performing volitional tasks or engaging in activities involving non-paralyzed muscles [5–8]. This phenomenon is frequently referred to as 'discomplete' SCI [9, 10], although this classification may create confusion. Consequently, when activities associated with residual motor control are detected through electrophysiological measurements, patients classified as having a complete injury according to the AIS (American Spinal Injury Association Impairment Scale) may indeed exhibit characteristics of discomplete injury. This suggests that clinically diagnosed patients with complete SCI may still possess the capacity to generate a certain level of volitional muscle activity below the injury level. Although the practicality of such activities may have been limited previously, advancements in rehabilitation and repair technologies now permit these activities to assist or restore function [11–15], even years after-injury. This finding offers new opportunities for the rehabilitation of SCI patients and emphasizes the significance of electrophysiological measurements in evaluating the extent of SCI and the potential for functional recovery.

Assessing the residual connections in the leg neural circuits of patients with complete SCI, using surface electromyography (sEMG) has demonstrated greater sensitivity than other electrophysiological techniques [14, 16]. However, it is important to note that many patients with complete SCI have not attempted to activate their paralyzed muscles for extended periods; this may hinder their residual descending axons from achieving optimal activation during the initial sEMG assessment, resulting in challenges in demonstrating residual motor function in severely paralyzed patients. Although studies have indicated that following several weeks to months of intensive training, patients demonstrate increased sEMG activity, thus confirming the presence of unknown residual nerve fibers at the injury site [14, 17], the associated time and healthcare costs are substantial, rendering this method challenging to implement and promote widely.

In light of the current state of assessment, we undertook a study entitled 'Optimizing sEMG Assessment of Residual Motor Function in Patients with Severe Spinal Cord Injury.' This study consists of two parts: the first part involves a passive approach, in which rapid, extensive passive movements are implemented to instantly adjust the excitability of spinal circuits, aiming to elicit enhanced sEMG responses from patients during tasks requiring volitional control [18]. The second part employs an active methodology, utilizing VR technology to enhance patients' kinesthetic awareness and motor imagery (MI) capabilities, with the goal of enhancing the brain's output of volitional motor signals and thereby increasing the sensitivity of detecting residual sEMGmotor signals. This paper will provide a detailed account of the research content of the second part.

Studies have demonstrated that MI deficits exist after spinal cord injury, and lesion level and completeness, time interval from lesion onset, and pain doinfluence MI [19, 20]. C.-J. Olsson [20] conducted a MI study involving a patient with chronic, complete spinal cord injury. The results indicated that the patient could activate the premotor cortex only during wheelchair obstacle courses. For stair walking, the patient engaged the inferior frontal cortex and parietal cortex. Although the specific tasks differed, the results were similar to those of a normal control group. The study concluded that complex motor representations may not be preserved after spinal cord injury, suggesting that MI is contingent on the body's current capacity to execute tasks. Research by Scandola et al. found that SCI subjects scored significantly lower on the MI questionnaire relative to a healthy control group when asked about their subjective, conscious experiences of MI. Notably, the difference between SCI subjects and the control group did not emerge under third-person perspective conditions but became evident only under first-person perspective conditions [21]. Our previous study also found similar results, as patients with chronic complete SCI reported an inability to imagine the sensation of executing volitional movements of the lower limbs, particularly at the distal joints, and expressed uncertainty about how to attempt such movements. In these cases, patients typically exerted force throughout their bodies but still could not elicit volitional movemen sEMG activity [18, 22].

Both afferent and efferent pathways exhibit distinct functions in MI and support the concept of an inherent connection between action imagery and action execution. Brain networks involved in body-related perception and advanced cognitive processing of body-related information, such as action recognition, interpersonal space perception, and MI, depend on a continuous and bidirectional exchange of information between the brain and the body, particularly the integration of motor commands and somatosensory feedback [23]. After spinal cord injury, the significant disconnection between the brain and the body results in impairments in motor cognitive abilities, including MI, spatial perception, and embodied cognition [19, 24–26].

An effective way to enhance MI is through action observation, which entails observing body movements associated with the MI task [27, 28]. Studies have shown that virtual reality (VR)-based action observation can enhance MI performance by providing enhanced visual feedback and a heightened sense of embodiment (SOE) [29, 30]. Specifically, Lakshminarayanan et al. [30] found that participants exhibited a stronger kinesthetic MI (KMI)-induced event-related desynchronization (ERD) in a VR environment relative to conditions lacking visual representation. When participants observed motor tasks in an immersive VR environment, the strong sense of body ownership induced in the VR setting could enhance the KMI of the body parts engaged in task execution [31, 32]. This finding provides compelling evidence for the use of VR technology to improve MI abilities in stroke patients.

In VR technology, the SOE has been extensively studied as a critical element in enhancing MI through sensory illusions [29]. SOE refers to a collection of sensations pertaining to bodily ownership and motor control, consisting of three components: self-location, the sense of agency, and the sense of body ownership [33]. Self-location describes the state in which individuals perceive themselves as being located within their biological body or virtual avatar. This perception is largely influenced by the visual spatial perspective, as visual information is typically egocentric. Studies have demonstrated that, compared to a third-person perspective, a first-person perspective elicits stronger physiological responses in reaction to perceived bodily threats [34, 35]. Additionally, synchronized visuotactile congruence—where tactile stimuli are experienced from an egocentric viewpoint—can further enhance the sense of self-location.

The sense of agency refers to the subjective experience of overall movement control, encompassing awareness of control, intention, movement selection, and volition [36]. This perception emerges from the comparison between predicted sensory outcomes and actual sensory outcomes [37]. When the predicted outcomes of actions align with the actual results, as observed in the synchronization of visual movement during active motion, individuals feel as though they are in control of those actions. In VR environments, the sense of agency is readily evoked when participants' movements are mapped onto a virtual body in real-time or near-real-time [38].

The sense of body ownership refers to the psychological state in which individuals perceive a body as an integral part of themselves [39]. It encompasses a sense of possession, implying that the body is experienced as the source of sensory input [40]. From a bottom-up perspective, enhancing sensory congruence between the biological body and the virtual avatar—such as through synchronized visuotactile and visuoproprioceptive inputs—can significantly enhance the sense of body ownership. In contrast, top-down influences facilitate the perception of ownership over the virtual body by maximizing the morphological similarity between the biological and virtual entities. Furthermore, limb movements are more directly correlated with the sense of agency and have been shown to further augment embodiment. The illusory effects of these movements may exceed those of visuotactile stimuli, as they concurrently engage both the sense of agency and body ownership [39–41].

In the virtual realm, an individual's self-representation not only serves as a reference point for visual motor tasks but may also possess behavioral significance in its form. Previous research on action observation and MI indicates that visual stimuli modifying movement parameters—such as force, muscle contraction characteristics, limb movement trajectories, and object mass—can modulate corticospinal excitability or activity in the primary motor cortex [42–44].

Previous research has demonstrated that patients with severe lower limb paralysis experience a pronounced sense of body ownership and vivid movement illusions in immersive VR environments, which can significantly enhance MI performance in stroke patients [45]. Furthermore, during a 7-day follow-up, the majority of patients reported frequently recalling VR scenarios and spontaneously engaging in movement practice, indicating that short-term VR training can assist patients in establishing stable and enduring motor memories. This memory effect persists after-training and exerts a positive influence on patients' MI capabilities. Even after the training concludes, patients retain memories of the training content and actively engage in related MI practices in their daily lives [45].

Therefore, the primary objective of this study is to investigate the immediate effects of this rehabilitation system on the residual motor control abilities of patients with complete lower limb paralysis resulting from SCI, thereby enhancing the sensitivity of sEMG for assessing residual function.

Participants and methods

General information

This study has received ethical approval from the institutional ethics committee and meets the ethical standards set out in the Declaration of Helsinki, and all participants provided informed consent after fully comprehending the study procedures. The study sample consisted of 12 patients with spinal cord injury, including 9 male and 3 female patients. The patients' ages ranged from 28 to 58 years, with a mean age of 39.92 years (SD ± 11.67 years). Their disease duration was 12 months or longer, with a mean duration of 23.25 months (SD ± 10.58 months). All patients were diagnosed with thoracic spinal cord injury with 10 patients classified as AIS A (motor/sensory complete) and 2 patients classified as AIS B ((motor complete/sensory incomplete) based on the International Standards for Neurological Classification of Spinal Cord

Injury (ISNCSCI). Patients with severe lower limb spasticity, concomitant traumatic brain injury, severe cognitive impairment hindering cooperation, epilepsy, other conditions affecting motor and sensory functions, or implanted pacemakers or other medical devices were excluded from this study. Subsequently, we conducted conventional EMG nerve conduction studies on the bilateral tibialis anterior muscles of all participants following the initial AIS classification and lesion level determination. The purpose of this step was to eliminate the possibility of conus/cauda equina lesions, accompanying peripheral nerve injuries, and pre-existing neurological conditions. Detailed records of patient age, time of injury, cause of injury, AIS classification, and motor level of the injury are presented in Supplmentary Table 1.

Virtual environment and training process

In Fig. 1, the virtual avatar assumed a seated afterure on a yoga mat with legs apart, while utilizing a VR head-mounted display (HMD) to offer a first-person perspective. The patient extended their unaffected forearm and wore a Myo armband, engaging in repeated, sustained, and controlled wrist dorsiflexion to activate and relax all forearm muscles. To enhance the accurate identification of sEMG signals, the sEMG electrodes were strategically positioned within the muscle groups, focusing on areas with larger muscle volume and minimal interference from neighboring muscle groups. The sEMG armband captured the forearm's sEMG signals to control the virtual avatar's ankle movements. Ropes were used to secure the avatar's feet to a chest filled with gold bars. Each patient aimed to bring these chests as close to their body as possible while performing wrist dorsiflexion exercises. Simultaneously, a virtual ankle dorsiflexion equivalent to the wrist movement was rendered in the VR scene. All participants utilized the Myo armband on their unaffected forearm in conjunction with the HTC Vive HMD. To ensure proper contact, individuals with slender arms utilized Myo-Sizing Clips (available at https://www.thingiverse.com/thing:04751471). The VR

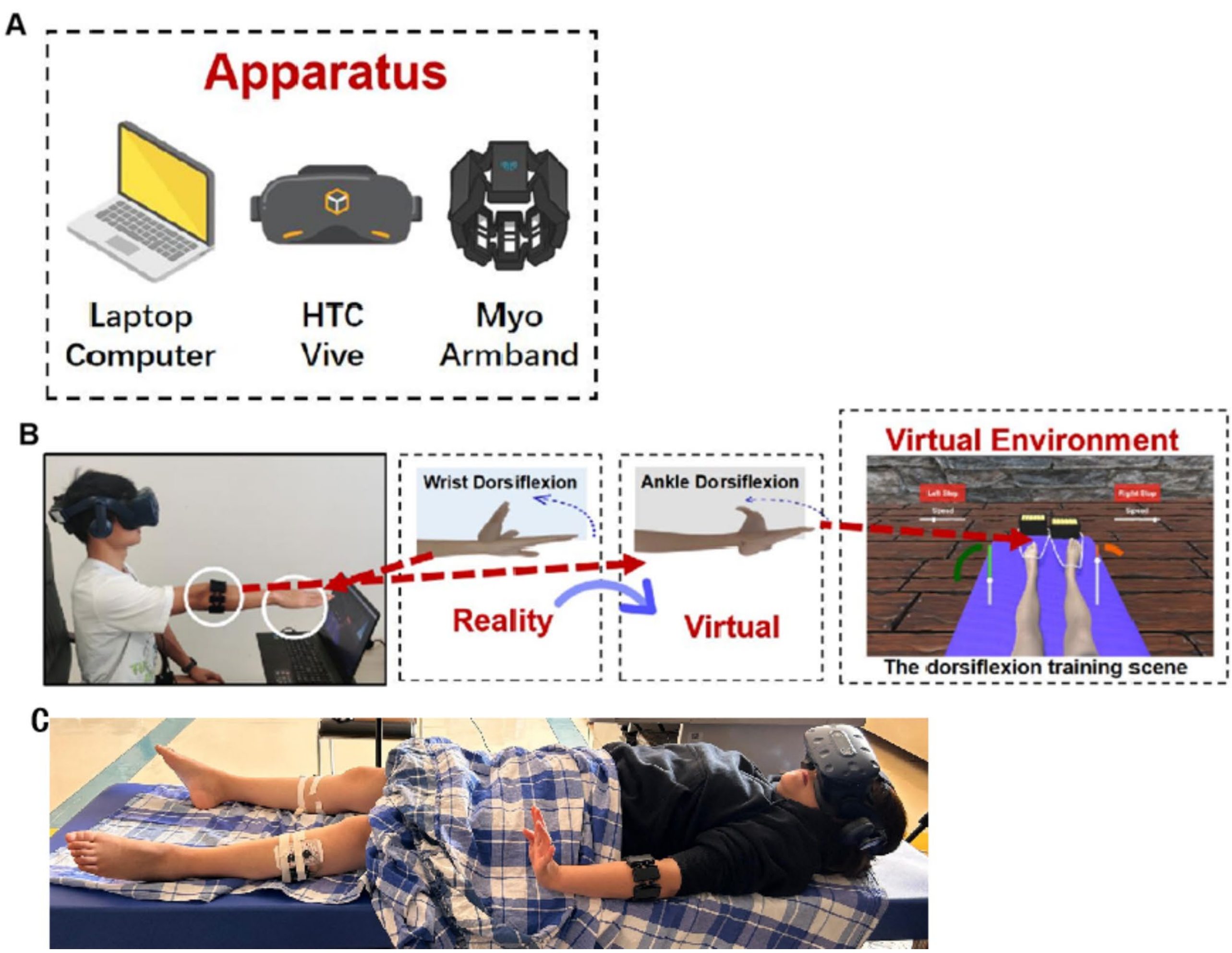

Fig. 1 VR System Equipment and Principles: (**A**) System Equipment; (**B**) Schematic Diagram of the Whole Experimental Device. (**C**) Patients with SCI performed VR training in supine position

training sessions lasted between 5 and 10 min. Patients were directed to move their wrist joints at a comfortable pace to govern the virtual ankle's motion in the VR scene, while mentally envisioning synchronized movements of an actual injured ankle.

Experimental design and procedure

Collection and analysis of sEMG data before and after VR training

The sEMG signals in this study were collected using the Noraxon 3.8.6 sEMG system (USA) to detect signals from the bilateral rectus femoris (RF), biceps femoris(BF), tibialis anterior(TIB), and gastrocnemius(GAS). Throughout the data acquisition process, a 12-bit analog-to-digital converter (ADC) with a sampling rate of 2000 Hz was employed, guaranteeing the continuity and accuracy of the acquired data. The sEMG data recording gain was set to 1000, while the bandpass frequency range was configured as 30–500 Hz, enabling it to accommodate the dynamic fluctuations observed in the sEMG signals.

The modified Brain Motor Control Assessment(BMCA) approach was utilized [46]. All movements were executed with the participants in a supine position(Fig. 1C). At the onset of the experiment, a 5-minute relaxation phase was conducted to establish a baseline state for the participants' muscles. Subsequently, the participants were instructed to perform volitional control tasks that entailed dorsiflexion and plantarflexion of the right ankle, as well as dorsiflexion of the left ankle. Throughout the entire process, participants were encouraged to exert their utmost effort, even in the absence of observable movement.

Each task had a fixed duration of 1 min, but the experimenter adjusted the number of action instructions flexibly based on the participants' individual conditions. Owing to variations in participants' fatigue levels, some were capable of completing the instructed tasks within 1 min, while others may have necessitated two sessions to accomplish the tasks, while still adhering to the total time of 1 min. A 1-minute rest period was allocated between two sessions, and a 2-minute rest period was allocated between tasks involving the left and right feet to ensure participants had sufficient recovery time.

Data synchronization was ensured by the experimenter through manual length marking. Upon completion of each movement phase, the experimenter released the marking button and provided feedback to the participants regarding the successful completion of the task maintenance phase. Furthermore, the recorded data were processed to meet the requirement of a minimum 5-second analysis window.

In the event of muscle spasms occurring during the experiment, the procedure was promptly paused until the muscles relaxed, and then resumed. In the case of spasms occurring during the data recording process, the respective data were excluded. Throughout the entire experiment, these specific events were continuously documented to ensure the accuracy and reliability of the data.

sEMG data were collected and analyzed during the VR training session

The sEMG parameters during VR training remained consistent with those before and after VR training, and they were continuously recorded throughout the entire VR training session until its completion.

sEMG signal processing

To acquire the intensity information of surface electromyographic signals, we applied full-wave rectification and computed the root mean square (RMS) value of the amplitude. The baseline noise level was determined by calculating the average amplitude during the initial 0 to 5 s of the response, which corresponds to the silent period.

Conduct descriptive analysis of the data: identifying active channels Visual inspection rating. Conducting visual inspection for all trials of each channel proves to be an effective analytical approach. The collected channels are then sorted from 1 to 5 based on the observed activity patterns, following a ranking system similar to the one used by Calancie et al. [47, 48] (refer to Supplmentary Fig. 1). While ranking is subjective, the use of guidelines to rank the channels ensures the reliability of the results. As depicted below:

1) No apparent activity; baseline noise
2) Sparse MUAP detected, characterized by single spikes rather than bursts, but no clear correlation with motor cues.
3) Burst activity detected, but no clear correlation with motor cues.
4) Burst activity related to cues but lacks precision (several false positives) or repeatability.
5) Repeated bursting visible activity, exhibiting good correlation within 2–3 cues.

Trajectories conforming to each criterion are shown in Supplmentary Fig. 1. Channels ranked 4 or 5 are referred to as active channels for subsequent analysis.

Conduct quantitative analysis of the amplitude of sEMG: identifying active channels

We subsequently defined bursts in the sEMG as signal segments with amplitudes that reached or exceeded 3μV. If the signal's amplitude was below 3μV, we interpreted its variations as potentially indicating an inadequate response to volitional movement attempts, as supported by previous studies [16, 49].

Adhering to instructions was imperative during the baseline and after VR training volitional tasks. Owing to the existence of delay phenomena in the initiation and termination of motor activity, we precisely defined the onset of burst duration. Specifically, we regarded the initiation of burst duration as the moment when the first positive burst occurred following the issuance of the command. We considered the burst to conclude when the signal returned to the baseline level and maintained stability for a duration of 300 milliseconds [50].

In order to evaluate the delay of continuous positive sEMG signals, we conducted measurements within a volitional trial window lasting 5 to 10 s. We further distinguished between peaks occurring within and outside of the cue period during the before and after-VR experiments. The cue period was defined as the time interval spanning 5 to 10 s, and active channels denoted peaks occurring within this designated cue cycle.

Counting the task-frequency of muscle activation channels

After identifying the active channels, it is necessary to subsequently determine the frequency of activation for each of these channels, which we refer to as task-frequency. When defining muscle activation task-frequency, we considered the presence of muscle activity in each task as a single activation l [18]. If a muscle was active across multiple tasks, such as the BF activated in both right and left ankle flexion-extension tasks, then two activations were counted for that muscle in this analysis. Finally, the task frequencies of each muscle involved were summed of each patient, resulting in the total task frequency counts for the before-VR, during-VR, and after-VR phases, respectively. See Table 1.

Counting the 5-rank activation frequency of muscle activation channels

After determining the task frequencies for each channel, we proceed to establish the 5-rank activation frequencies for these activated channels. When defining the 5-rank activation frequencies, we consider the presence of muscle activation, characterized by "repeated bursts of visible activity with good correlation within three or more cues," in each task as a single 5-level activation (see Supplmentary Fig. 1). If a muscle exhibits 5-rank activation in both left and right ankle flexion-extension tasks, for instance, the BF demonstrates 5-rank activation in both left and right ankle flexion-extension tasks, it is counted as having a 5-rank frequency of 2 in this analysis. If the muscle exhibits 5-level activation in one ankle task but 4-rank activation or no activation in the contralateral ankle task, it is counted as having a 5-rank frequency of 1 in this analysis. If the muscle demonstrates four-rank activation or no activation in both ankle flexion-extension tasks, it is also counted as having a 5-rank frequency of 0 in this context. Finally, the 5-rank activation frequencies of all tested muscles for each patient are summarized to obtain the total 5-rank frequency count for the before-VR, during-VR, and after-VR phases for each patient. See Table 1.

Comparing the differences in activation quantity at different time points

After counting the task-frequency and 5-rank activation frequency for the three phase, we will then proceed to compare the disparities in task-frequency and 5-rank activation frequency at three distinct time points: before-VR, during VR, and after VR.

Table 1 Task frequency and 5-rank frequency before, during, and after VR

subject	VR training time	task-frequency before VR	5-rank frequency	task-frequency during VR	5-rank frequency	task-frequency after VR	5-rank frequency	others
1	5	0	0	0	0	**1**	1	
2	5	0	0	**1**	1	**1**	0	
3	5	1	0	5	0	6	1	One week later, 3 channels were 5-rank activated.
4	5	0	0	0	0	0	0	The pain disappeared during VR training.
5	10	0	0	0	0	2	1	
6	10	0	0	**1**	1	3	3	
7	10	0	0	7	5	2	2	
8	10	0	0	2	2	0	0	
9	10	0	0	5	5	5	5	
10	10	2	1	0	0	14	14	All channels were activated after VR training.
11	10	6	2	6	6	3	2	The BF EMG after VR training showed high-amplitude mixed-phase.
12	10	10	3	13	11	5	5	During and after VR training, the L and R RF and BF both showed interference phase.
Total		19	6	40	31	42	28	

NA: Not Applicable

Statistical analysis

Since the count of task-frequency and 5-rank activation frequency are non-continuous data, we utilized a non-parametric hypothesis testing method, Wilcoxon Signed-Rank Test for Paired Samples, at a significance level of 0.05, to determine if there were significant differences between the two distributions.

Result

Task-frequency and 5-rank frequency (see Table 1)

Before VR training (baseline state), the total task frequency and the sum of 5-rank activation frequencies across all patients were 19 and 6, respectively. During the VR training, these figures rose to 40 and 31 for the total task frequency and the sum of 5-rank activation frequencies, respectively. After VR training, the total task frequency and the sum of 5-rank activation frequencies were 50 and 28, respectively. Statistical analysis revealed no statistically significant inter-group difference in task frequency before, during, and after VR (before vs. during: $p = 0.065$; before vs. after: $p = 0.191$; during vs. after: $p = 0.812$). However, the task activation frequencies during and after VR were more than double those before VR. Further statistical analysis indicated that the 5-rankl activation frequencies during and after VR were significantly higher than those before VR training, with statistically significant differences(before vs. during: $p = 0.029$; before vs. after: $p = 0.014$). Nevertheless, no statistically significant difference was observed between the 5-level activation frequencies during and before VR(during vs. after: $p = 0.474$).see Fig. 2.

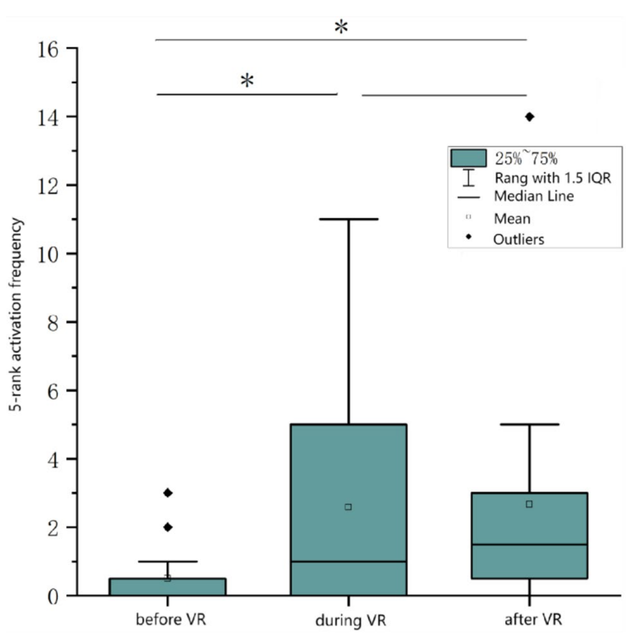

Fig. 2 Comparison of 5-rank activation frequencies was performed before VR training,during VR training and after VR training. In comparison to the before VR training, there was a notable and statistically significant increase in the number of 5-rank acitvation frequencies during and after VR training. However, no statistically significant difference was observed in the number of 5-rank acitvation frequencies between the during and after VR training conditions

Individual variations in patient channel activation

During both the VR training process and after-training, patients demonstrated diverse patterns of channel activation. Among them, three patients (P1,P5 and P10) did not exhibit channel activation during the VR training process, but they demonstrated activation after the training. One patient (P8) exhibited channel activation during the VR training process but did not demonstrate activation after-training. One patient (P4) did not exhibited channel activation throughout both the VR training process and after training. Moreover, seven patients (P2, P3, P6, P7, P9, P11, P12) exhibited channel activation throughout both the VR training process and after training.

Special case analysis

P3: Notably, patient P3 retained the ability to activate multiple channels when performing ankle-related tasks one week after the VR training (as shown in Fig. 3G-H). In retrospective inquiries about VR training recall, patients reported continuously recalling VR training scenarios during ankle-related tasks, which aided them in better executing the tasks—a fortuitous discovery.

P4: Patient P4 exhibited no volitional sEMG activation before, during, or after VR training. The patient has a history of lower limb neuropathic pain, with insufficient relief from medication. Before assessment, the patient experienced significant pain, which intensified intermittently, necessitating a change in position to side-lying for relief. To minimize experimental duration, a brief VR training protocol was implemented, consisting of 5 min of VR training for each ankle. During the VR training, the patient reported no pain at all; however, pain reemerged immediately after the conclusion of the training.

P6: During the VR training, Patient P6 exhibited a gradual increase in the frequency of right gastrocnemius muscle bursts, specifically at approximately 365 s while performing the right ankle task. The patient reported a growing sensation of embodiment towards the leg in the video and achieved sustained muscle control namely 5-rank activation around 480 s. Conversely, no comparable response was noted during the left ankle task, as depicted in Fig. 4.

P8: In the VR training for Patient P8's right ankle task, data recording commenced at approximately 350 s due to an initial oversight. Subsequent to the initiation of recording, approximately at 350 s, a period of continuous control of the right GAS muscle was observed, lasting approximately 32 s. Furthermore, at 440 s, P8 exhibited another episode of continuous control of the right GAS,

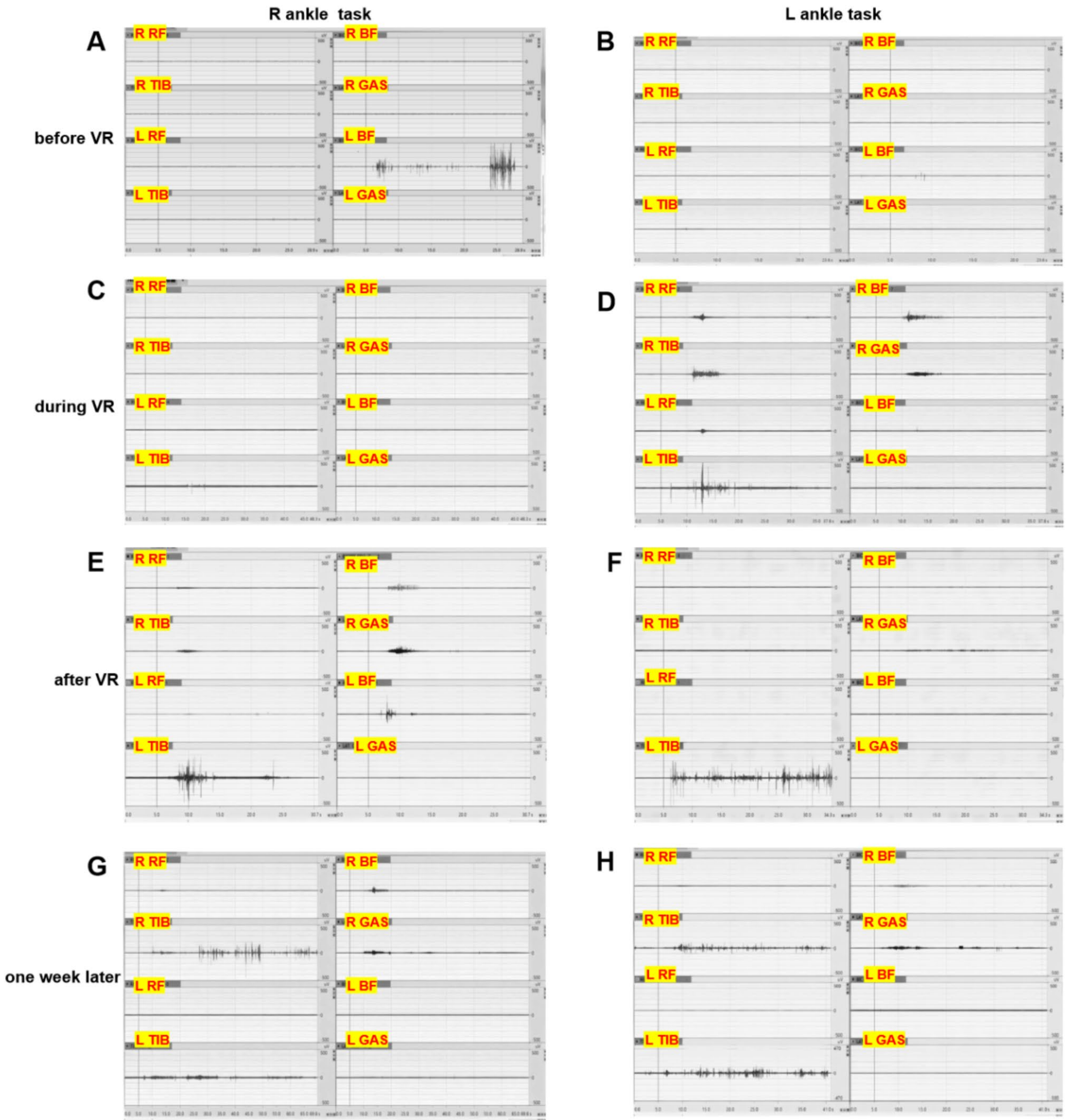

Fig. 3 sEMG recordings of P3 were obtained before,during (for 5 min),and after VR training. Before VR training, activation was observed in only the L BF during the R ankle task (**A**), while no muscle channels exhibited activation during the L ankle task (**B**). During VR training, no muscle activation was observed during the R ankle task (**C**); however, five muscle channels (RRF, RBF, RTIB, RGAS, LTIB) exhibited activation during the L ankle task (**D**). After VR training, five muscle channels (RBF, RTIB, RGAS, LBF, LTIB)exhibited activation during the R ankle task (**E**) and one muscle channel (LTIB) were activated during L ankle tasks (**F**). During the follow-up visit one week later, a total of seven task frequencies during both the R and L ankle tasks, four channel (RBF, RTIB, RGAS, LTIB) were activated during R ankle task (**G**) and three channles (RTIB, RGAS, LTIB) were activated during L ankle task (**H**)

which persisted for 36 s. Immediately thereafter, at 493 s, P8 achieved continuous control for an extended duration of 68 s, signifying adaptability and progress in the VR training. In P7's left ankle task VR training, an exceptional period of continuous control of the right GAS muscle was observed, lasting a remarkable duration of 330 s, commencing at approximately 200 s (as depicted in Fig. 5). The extended duration of control exemplifies P8's stability and concentration throughout the VR training.

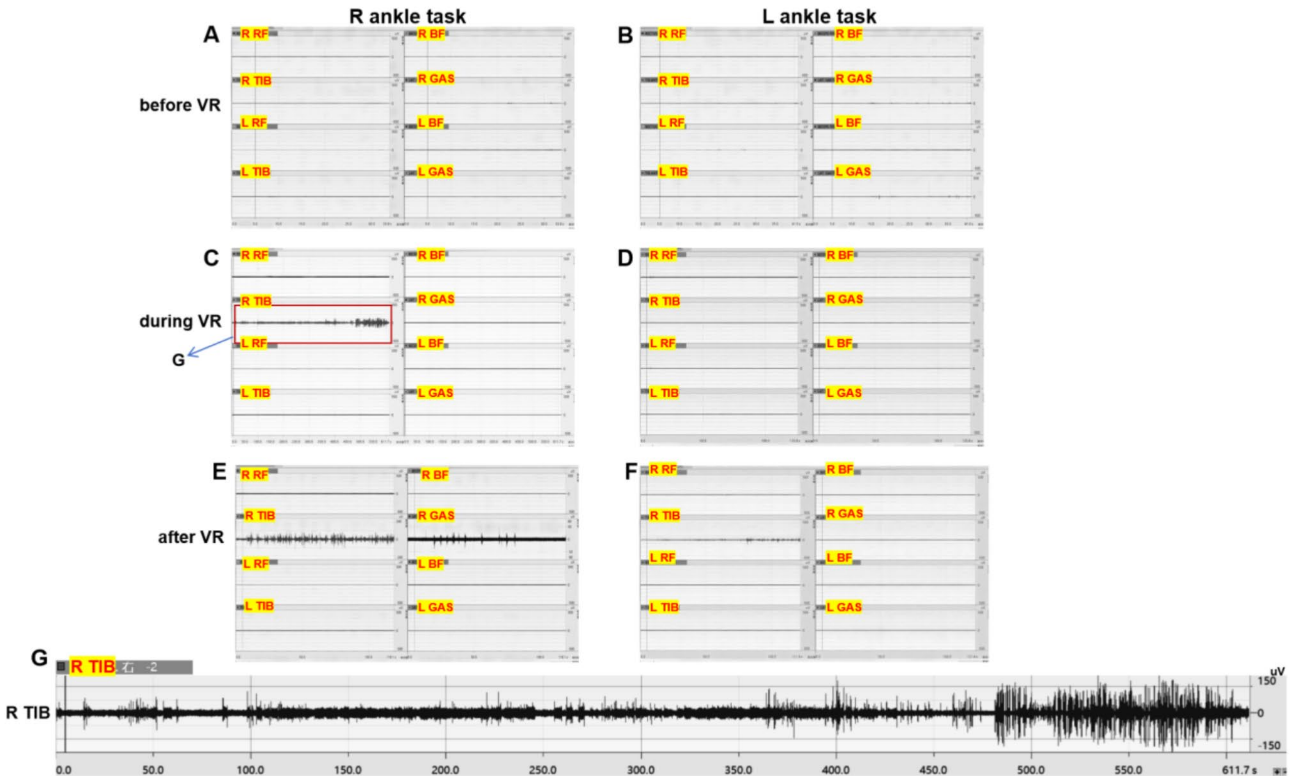

Fig. 4 sEMG recordings before VR training,during VR training (for 10 min),and after VR training for P6. Before VR training, there was no observed muscle activation during either the R or L ankle tasks (**A**, **B**). During VR training, the R TIB exhibited activation during the R ankle task (**C**), whereas no muscle activation was observed during the L ankle task (**D**). After VR training, muscle channels exhibited activation during both the R and L ankle tasks, resulting in a total of three task frequencies, both the R TIB and R GAS were activated during the R ankle task (**E**), whereas only the R TIB showed activation during the L ankle task (**F**). Figure **G** represents an amplified sEMG of the R TIB activated during the R ankle task in VR training. Notably, around 365 s, an escalating burst frequency in the R GAS channel can be observed, demonstrating sustained control until approximately 480 s

Furthermore, the patient reported to "feel as if she is there" during the later phases of the VR training.

P10: The baseline assessment before VR training included two task frequencies (one for the left GAS and one for the right GAS, with the right GAS exhibiting a 5-rank activation. During the VR training, there was no activation recorded in any channel; however, following the VR training, both the task frequency and the 5-rank frequency reached 14 times. The patient reported an increasing ease in controlling limb movement from the onset of VR training through the after-training assessment period. Supplmentary Fig. 2.

P11: Although the task frequency and 5-rank frequency decreased after the VR training, the after-VR sEMG assessment revealed sustained high-amplitude volitional sEMG bursts in the left BF for 4 min, which resembled the mixed pattern observed during moderate volitional muscle contractions in healthy individuals. This pattern indicated an increase in the number of active motor units, with some areas displaying densely packed potentials while others showed sparse activity, allowing for the baseline pattern to be discerned. The patient reported experiencing a sensation of his feet moving during the VR training, reminiscent of previous dreams. In the sEMG assessment following the VR training, the patient expressed an increasing sense of control over his limbs and requested an extended duration for the assessment. Continuous EMG bursts began to appear at 65 s, with a significant increase in sEMG amplitude noted at 95 s. Self-regulation persisted for 4 min, at which point the patient reported fatigue and requested to stop. Supplmentary Fig. 3.

P12: sEMG assessments before, during, and after VR training revealed several task frequencies and 5-rank frequencies. Notably, during and after VR training, the sEMG evaluations showed that the RF and BF on both sides exhibited interference patterns during corresponding side tasks, resembling the maximal muscle contractions observed in healthy individuals. Specifically, the number of excited motor units was maximized, the firing rates were highest, and overlapping interference patterns were present. Supplmentary Fig. 4.

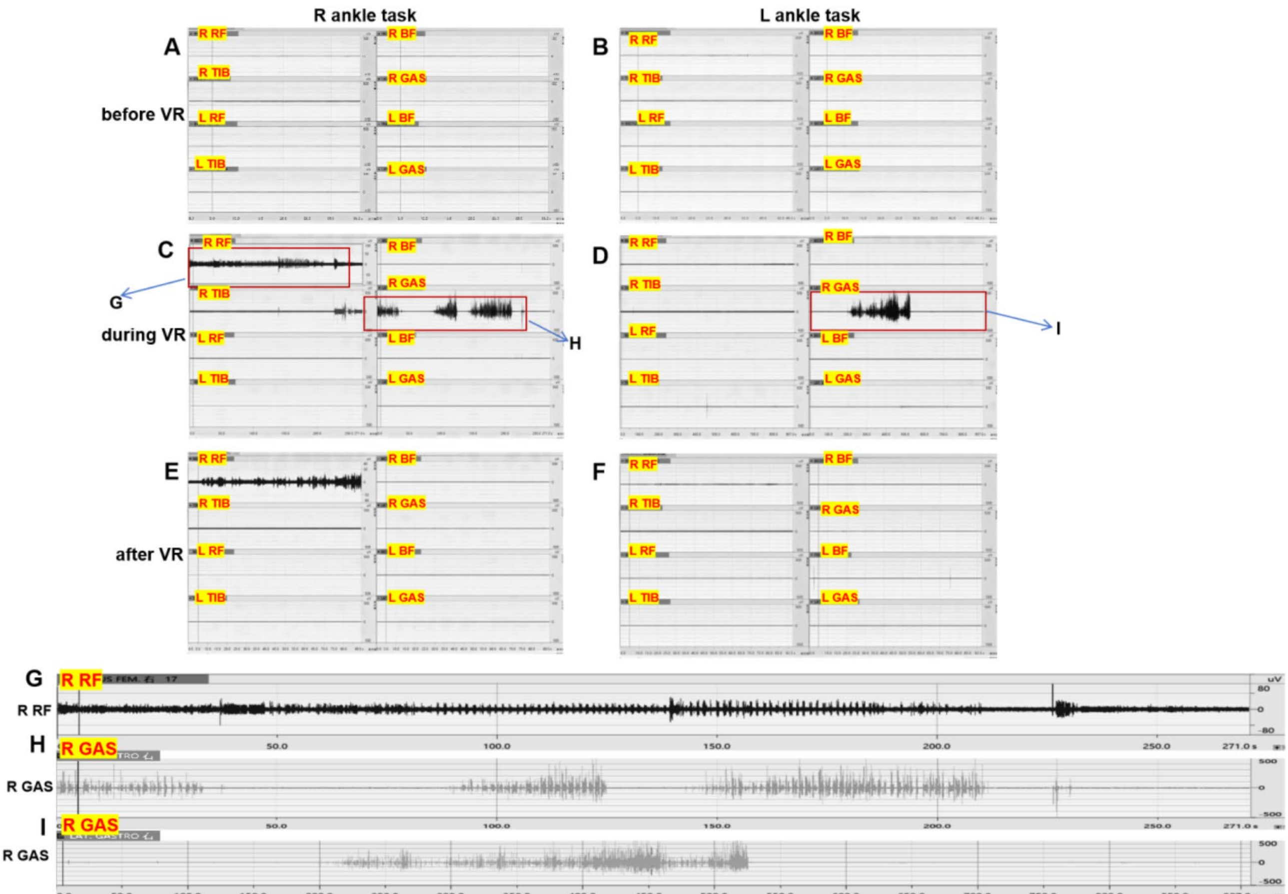

Fig. 5 sEMG recordings of P8 before VR training,during VR training (for 10 min),and after VR training. Before VR training, no muscle activation was observed during both the R and left ankle tasks (**A**, **B**). However, during VR training, the R RF and R GAS exhibited activation specifically during the R ankle task (**C**), while the sEMG signal of the R TIB indicated an sEMG artifact, implying non-volitional muscle activity. Notably, during the L ankle task, activation of the R GAS was observed (**D**). After VR training, the R RF exhibited activation during the R ankle task (**E**), whereas no muscle activation was observed during the L ankle task (**F**). Figure G represents an enlarged sEMG signal of the R RF activated during the R ankle task in VR training, Figure H depicts an enlarged sEMG signal of the R GAS activated during the R ankle task, and Figure I illustrates an enlarged sEMG signal of the R GAS activated during the R ankle task, demonstrating intermittent continuous control in all three muscle channels

Discussion

This study utilizes VR technology to enhance patients' perception and control of movement, thereby improving the immediate motor function of individuals with complete paralysis resulting from SCI and increasing the sensitivity of sEMG in assessing residual motor function. By employing motion signals from functional upper limbs, the research presents an innovative method for interaction with a virtual environment. Although the results demonstrate considerable individual variability, the majority of patients exhibited significant sEMG effects during or after VR training, indicating an increase in activation frequency (task frequency) or an enhancement in activation quality (5-rank frequency). Only one patient with severe lower limb neuropathic pain displayed no volitional sEMG activation at baseline, during VR training, or after VR training; however, this patient's pain subsided during the VR training process.

Training time

The results of this study indicated that among the four patients who underwent 5 min of VR training, two did not exhibit any sEMG activity, one exhibited discrete bursts of sEMG activity, and the other exhibited continuous but weak bursts of sEMG activity. In contrast, among the eight patients who underwent 10 min of VR training, with the exception of two who did not exhibit any sEMG activity, the remaining 6 all demonstrated significant and sustained bursts of sEMG activity, primarily occurring after 5 min of training. Three SCI patients reported an increasing SOE, perceiving the foot in the video as their own and experiencing a heightened sense of immersion as the training progressed. A patient (P10) did not demonstrate any sEMG activity during VR training; however, after VR training, the patient exhibited multiple activation channels, all at 5-rank activation. The patient reported that from the onset of VR training to the sEMG assessment afterward, movement control became progressively easier. We propose that the absence of induced sEMG activity during VR training was due to the patient's emphasis on action observation and learning rather than imitation. The cumulative effects of the patient's learning were evident in the assessment conducted after VR training. Other patients may have shown a greater inclination towards action observation and imitation, which could have facilitated the induction of sEMG activity during VR training.

Our result suggests that in the fully immersive state facilitated by VR, patients can experience notable body illusions, kinesthetic illusions and sense of movement control. However, these findings contrast with the study conducted by Pozeg et al. [51], which revealed that SCI patients exhibit a reduced sensitivity to multisensory stimuli inducing the illusion of ownership over a virtual leg compared to healthy individuals.

In our study, the vivid body illusions and motor illusions experienced by some patients did not manifest immediately but gradually emerged during the latter half of the VR training session, approximately after 5 min. Concurrently, the elicitation of sEMG activity also occurred during the latter half, providing further evidence of the reduced sensitivity of SCI patients to multisensory stimuli inducing the illusion of ownership over a virtual leg. This observation suggests that a certain amount of time is required to achieve a "hypnotic" effect [52]. By appropriately extending the duration of VR training, it is possible to effectively enhance the intensity and persistence of body illusions.

Morphological similarity between biological entities and virtual entities

Multi-sensory stimulation and morphological similarity play a crucial role in enhancing the sense of body ownership, thereby impacting users' immersion and the behavioral performance of their virtual avatars [40]. By enhancing the correlation between physical and virtual stimuli and designing avatars that are morphologically similar to users, the virtual experience can be improved.

Previous literature has demonstrated that changes in motion parameters, including force requirements, muscle contraction characteristics, limb movement trajectories, and visual stimuli associated with object mass, can modulate corticospinal excitability or activity in the primary motor cortex during action observation and MI [42–44].

Taking the above factors into consideration, in our design of virtual scenarios, we present the complete lower limbs without clothing and realistically portray the dynamic changes in lower limb muscle movements. Additionally, we design ankle movement as a transitive action where ankle dorsiflexion is employed to pull a box of gold. We hypothesize that in the VR scenario, the dynamic contraction of lower limb muscles, along with the movement of the gold box, will collectively generate intense visual stimuli, guiding participants to experience profound illusions.

In contrast, other VR scenario designs, such as the study conducted by Borrego et al. [35], involve avatars with their lower limbs covered by pants and shoes, which conceal muscle and skin cues associated with the applied force. This could account for the weaker sense of body illusion observed in their study.

Sense of motor control

VR technology plays a crucial role in modulating the sense of body ownership and enhancing immersion through the integration of multi-sensory inputs and improved interactions between the user's body and the virtual environment [53–57]. Control over movement and the close correlation between physical movements and avatar movements are particularly essential for enhancing users' sense of presence and illusion effects [38, 58].

In our designed system, we innovatively utilized the movement of the unaffected wrist to control the actions of the virtual foot, thereby providing patients with motor complete SCI the opportunity to experience active control within a virtual environment. Although the experimental design lacked a systematic questionnaire to gather patients' subjective evaluations, feedback from patients' sporadic self-reports indicated that a common experience among them was a heightened sense of body ownership, vivid kinesthetic illusion, and an increasing sense of control as training progressed. Most patients exhibited 5 rank activation during VR training, suggesting that they acquired some degree of continuous motor control.

Promoting intrinsic motivation

In our designed system, we utilize the movement of the unaffected wrist to control the actions of the virtual foot, with the aim of equipping patients with the capability and confidence to successfully accomplish tasks. Self-Determination Theory (SDT) provides a framework for comprehending the two distinct forms of motivation: intrinsic motivation, originating from inherent enjoyment and interest in specific activities, and extrinsic motivation, which depends on external factors like rewards or threats to enhance performance [59].

It is worth noting that the primary intention behind our system design was not to pursue gamification effects, but rather to prioritize the simplicity and practicality of the scenario. In our previous research involving stroke patients, we observed that stroke patients exhibited a high level of acceptance towards the system and expressed their willingness to use it again, despite not perceiving the system itself as a source of entertainment [45].

According to Self-Determination Theory, when individuals' needs for ability, relatedness, and autonomy are satisfied, they will experience a deep sense of self-determination. Although these psychological factors do not directly lead to immediate functional improvements, they are closely linked to the observed recovery of motor function. Although we have not conducted direct scale assessments on patients with SCI, we have reason to speculate that the value experience of mobility is similar between stroke patients and SCI patients [45].

Improving MI and motor memory

SCI not only affects the perception of body representation [19, 60–65], but also profoundly impairs the ability to perform MI from a first-person perspective [21, 66], highlighting the crucial role of continuous and bidirectional information flow between the brain and body in higher-order cognitive processing [23, 67].

Similar to our previous research, patients with complete motor SCI in this study generally reported being unable to imagine the sensation of performing ankle joint movements when attempting volitional ankle joint movement. Patients often exerted force throughout their bodies, resulting in minimal volitional sEMG activity. However, immediate sEMG assessments following VR training revealed significant changes in 10 out of 12 patients, with 9 patients exhibiting 5-level activation channels. These findings suggest that VR training can enhance patients' task-related MI capabilities and motor memory functions, thereby improving their motor control. Notably, in a follow-up assessment one week later, one patient unexpectedly demonstrated improved volitional sEMG activity. The patient reported that while performing the ankle task, he recalled scenes from the VR training conducted a week earlier, which enabled him to make a more concerted effort in executing the ankle movement. This case suggests that VR training may contribute to enhancing long-term motor memory in patients.

P4 was the only patient who showed no observable motor effects from the VR intervention. Studies suggest that the higher the lesion level, the worse the MI performance, with patients with complete injuries demonstrating poorer MI performance than those with incomplete injuries [19]. However, the lesion level and severity in this patient were not worse than in other patients; yet this patient experienced severe neuropathic pain, a symptom absent in the other patients. Scandal et al. found that patients with chronic lesions and pain exhibited worse MI performance compared to SCI patients without pain, and in the presence of pain, MI declines over time, with a marked reduction in kinesthetic MI ability [19]. Therefore, we believe that the lack of motor improvement in this patient following VR intervention is related to their severe neuropathic pain, which likely exacerbated their diminished MI performance.

Although P4 did not benefit from motor function improvements following the VR intervention, the patient experienced significant pain relief throughout the VR training sessions. This aligns with previous studies [68–72]. Pain management, as an important application of VR technology in SCI patients, has garnered significant attention in recent research. Currently, most studies focus on patients with complete SCI or those with severe motor function limitations [68–72], with several studies also exploring the short-term effects of VR on neuropathic pain. These studies primarily assess the short-term impact of VR in reducing neuropathic pain in SCI patients. Although the current body of research and sample sizes remain relatively small, these preliminary findings demonstrate promising potential.

Limitations

As a preliminary exploratory study, we acknowledge the limitation of not collecting subjective evaluation indicators from patients. Nonetheless, prior research has demonstrated that VR systems can effectively induce vivid body illusions and kinesthetic illusions in stroke patients with ankle paralysis, resulting in an enhanced sense of agency and positive effects on MI and motor memory, while also being well-received by patients [45].

Despite the distinct causes of motor impairment in patients with SCI and stroke, the research results of stroke patients allow us to reasonably speculate that the system may exhibit certain similarities in promoting bodily illusions and kinesthetic illusions in the case of complete SCI.

Secondly, the research results are somewhat weakened in terms of statistical power and persuasiveness due to the relatively small sample size of patients. Furthermore, a small sample size can result in deviations or instability in the research results, thus limiting the generalizability and applicability of the research conclusions.

However, the electrophysiological results of this study still offer valuable insights and potential applications in utilizing VR technology for the rehabilitation treatment of patients with complete spinal cord motor injury, establishing a beneficial foundation for future research and exploration.

Finally, as the purpose of this study was to enhance the sensitivity of sEMG in assessing residual motor function rather than to investigate clinical treatment outcomes, evaluations were performed immediately following a single VR training session. Given the positive effects observed in the results of this study, a future study focused on clinical treatment outcomes is planned. In this future study, patients will undergo multiple treatment sessions rather than a single session, enabling a more thorough assessment of the clinical outcomes.

Conclusion

This study aimed to enhance the residual motor function of patients with complete motor SCI by utilizing an interactive virtual foot and ankle rehabilitation system, thereby improving the sensitivity of sEMG assessment. The system employed signals from the unaffected upper limbs to control the virtual environment. The effectiveness of the system relies on the SOE in VR, encompassing perceptions of self-location, sense of control, and body ownership. These perceptions greatly enhance patients' bodily illusions, kinesthetic illusions, and MI abilities. The study revealed that, for patients with motor dysfunction, the ability to control movement takes precedence over the richness of the virtual scene. This ensures a heightened sense of presence for the subjects and directs their attention towards the interactive level.

When designing VR interventions for rehabilitation, it is crucial to have a comprehensive understanding of how different sensory and motor manipulations in VR impact neural processes. This is vital to ensure the full utilization of VR technology and maximize its effectiveness in the rehabilitation environment. By exploring this interactive mechanism, we can gain a better understanding of how to enhance the recovery of patients' motor functions through VR technology and provide valuable insights for future rehabilitation research.

Abbreviations

ADC	Analog-to-digital converter
AIS	American Spinal Injury Association Impairment Scale
BF	Biceps femoris
BMCA	Brain Motor Control Assessment
ERD	Event-related desynchronization
GAS	Gastrocnemius
HMD	Head-mounted display
ISNCSCI	International Standards for Neurological Classification of Spinal Cord Injury
KMI	Kinesthetic MI
L	Left
MI	MI
R	Right
RF	Rectus femoris
RMS	Root mean square
SCI	Spinal cord injury
sEMG	Surface electromyography
SOE	Sense of embodiment
TIB	Tibialis anterior
VR	Virtual reality

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Author contributions

Yanqing Xiao carried out the studies, participated in collecting data, and drafted the manuscript. Hongming Bai, Guiyun Song, Hanming Wang, Jiasheng Rao, Aimin Hao performed the statistical analysis and participated in its design, Jia zheng, Yang Gao, and Xiaoguang Li participated in acquisition, analysis, or interpretation of data and draft the manuscript. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

The study procedures were approved by the Medical Ethics Committee of China Rehabilitation Research Center (approval No. 2020-014-1, April 1, 2020) and were conducted with the informed consent of all participants.

Consent for publication

In the experiment, participants agreed to have their experimental data used for publication, and this part of the agreement is written in the informed consent form(approval No. 2020-014-1, April 1, 2020) for the experiment.

Competing interests

The authors declare no competing interests.

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