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REVIEW

Virtual Reality Interventions for Spinal Cord Injury-Related Neuropathic Pain: A Comprehensive Scoping Review of Multidimensional Outcomes

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Background: Virtual reality (VR) technology represents a novel non-pharmacological intervention demonstrating unique advantages in treating neuropathic pain (NP) following spinal cord injury (SCI). However, systematic clinical guidelines for its application remain lacking.

Objective: To systematically sort out the application patterns of VR in SCI-NP treatment, elucidate its underlying mechanisms of action, evaluate its advantages and limitations, and provide evidence-based recommendations for SCI-NP rehabilitation practice.

Methods: Following PRISMA scoping review protocols, we conducted a comprehensive search. Relevant literature was retrieved from PubMed, Cochrane Library databases, and Web of Science spanning from January 2005 to February 2025, using search terms including "virtual reality", "VR", "virtual walking", "spinal cord injury/SCI", "neuropathic pain", "central pain", "neuralgia", "chronic pain", and "pain." Studies examining VR applications in SCI-NP, including experimental and clinical investigations, were included. Narrative synthesis was employed to summarize VR application characteristics and therapeutic outcomes.

Results: Of the 126 articles retrieved, we included 15 articles involving more than 400 participants. Research designs encompassed randomized controlled trials (n=8), clinical trials (n=2), pilot studies (n=2), feasibility studies (n=2), and exploratory study (n=1). Assessment parameters included pain intensity, pain characteristics, pain interference, emotional status, and immersion experience. Twelve of 15 studies reported significant improvements in neuropathic pain intensity, while most studies assessing pain characteristics, pain Interference, emotional status and intervention quality demonstrated positive effects. However, given the methodological constraints of most studies, such as limited sample sizes, incomplete assessment measures, and insufficient follow-up durations, the widespread use and long-term effectiveness of VR intervention still require further validation.

Conclusion: Current evidence suggests VR technology may serve as an effective adjunct to, rather than replacement for, conventional treatment. Despite limited evidence, VR demonstrates promising analgesic efficacy and emotional enhancement potential in SCI-NP management. Critical knowledge gaps were identified regarding intervention modalities, treatment duration, and participant characteristics, providing recommendations for future research focusing on intervention protocol standardization, outcome measure harmonization, and mechanistic understanding advancement.

Keywords: spinal cord injury, central pain, chronic pain, immersive technology, pain management, scoping review

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Introduction

Spinal cord injury (SCI) represents a devastating neurological condition impairing multiple functional domains, including sensation, motor function, reflexes, and autonomic regulation,[1] while simultaneously precipitating numerous complications, among which pain is particularly significant. Evidence suggests that roughly two-thirds of individuals with SCI experience pain,[2] with neuropathic pain (NP) constituting the predominant pain phenotype, affecting 53% of SCI patients[3] and establishing itself as one of the most challenging post-injury complications.

SCI-related neuropathic pain (SCI-NP) predominantly manifests within areas of sensory impairment surrounding or below the injury site. SCI-NP is classified as "at-level" pain, experienced at or within three dermatomes of the neurological trauma level, typically emerging shortly after SCI and encompassing both central and peripheral components; or "below-level" pain, experienced more than three dermatomes below the neurological trauma level, which predominantly has central origins and emerges during the chronification process.[4]

The cardinal features of NP include spontaneous pain, hyperalgesia, allodynia and dysesthesia.[5] Spontaneous pain is defined as pain that occurs in the absence of identifiable external stimuli; hyperalgesia represents an abnormally enhanced and prolonged pain response to noxious stimuli; allodynia is characterized by pain evoked by normally innocuous stimuli; and dysesthesia encompasses altered sensory perception with either heightened or diminished stimulus sensitivity. This pain fundamentally differs from musculoskeletal pain, with patients characteristically reporting burning, shooting, pricking, pins and needles, squeezing, or freezing pain.[4] Its high prevalence, prolonged duration, reduced pain threshold, and intense pain experiences profoundly impact patients' emotional well-being and daily functioning, leading to fatigue, anxiety, depression, and sleep disturbances.[6] Compared with patients suffering from other types of chronic pain, those with chronic NP typically experience greater functional impairment and reduced quality of life.[5]

The specific mechanisms underlying SCI-NP development remain incompletely understood, though they are widely attributed to central sensitization and neuroplastic changes within the brain.[7] The International Association for the Study of Pain (IASP) defines central sensitisation as "Increased responsiveness of nociceptive neurons in the central nervous system to their normal or subthreshold afferent input".[8] This phenomenon is characterized by heightened neuronal excitability with contributing factors including altered neurotransmitter dynamics within the dorsal horn, diminished inhibitory interneuron activity, ion channel dysfunction (particularly involving sodium and calcium channels), and glial cell activation.[9] Beyond spinal-level alterations, supraspinal neurophysiological changes also contribute to NP development, including neuroplastic reorganization of the cerebral cortex and thalamocortical dysrhythmia.[10] Consequently, SCI-NP pathogenesis involves complex mechanisms across multiple levels of the neuraxis, encompassing central nervous system sensitization phenomena and the physiological and psychological influences of cortical plasticity changes.

Pharmacological intervention represents the primary therapeutic approach for SCI-NP management; however, this approach presents significant limitations including adverse reactions, limited efficacy, and the potential for drug resistance and dependence with long-term use.[6,11,12] Some non-pharmacological therapeutic approaches have gained increasing attention, including transcranial direct current stimulation (tDCS),[13] exercise therapy,[14] and cognitive behavioral therapy.[15] While studies suggest that these interventions demonstrate potential benefits, the quality of supporting evidence remains generally low, necessitating additional high-quality randomized controlled trials (RCT) to establish their clinical efficacy. In this context, virtual reality (VR) technology offers a non-pharmacological, non-invasive adjunctive treatment modality with promising potential for both short-term and long-term symptom improvement and pain reduction.[16]

VR represents a computer-generated technology that replaces real-world sensory input by generating immersive three-dimensional environments through computational simulation.[17] Users experience immersion and presence within these virtual environments. VR technology has evolved from early computer screen-based systems to sophisticated multi-device platforms. Contemporary VR systems integrate multiple components, including head-mounted displays (HMDs), sensory input devices, noise-canceling audio systems, and motion tracking sensors, which collectively generate realistic immersive experiences. The technology is characterized by cost-effectiveness, high accessibility, reusability, and capacity for personalized customization. These attributes have facilitated its widespread adoption in SCI-NP management,[16] where VR demonstrates potential therapeutic benefit.

Despite the significant challenges in SCI-NP management and emerging data supporting VR as a viable therapeutic approach, the literature examining VR interventions for SCI-NP remains limited in quality and quantity. This review seeks to identify and synthesize the existing evidence foundation, present findings that may provide guidance for clinical practice, evaluate the current state of empirical evidence, analyze knowledge gaps, and provide recommendations for future research directions in this field. In contrast to previous studies that have focused exclusively on pain intensity modifications, this review adopts a multidimensional analytical framework encompassing pain intensity, pain quality, pain interference, emotional responses, and intervention quality outcomes. This comprehensive approach facilitates a deeper understanding of VR's potential therapeutic value and clinical utility in SCI-NP management, thereby providing more thorough guidance for future research endeavors in this field.

Methods

Search Strategy

The present investigation utilized a scoping review approach, conforming to the JBI methodological framework and the PRISMA extension for Scoping Reviews reporting guidelines. A systematic search was performed across three databases (PubMed, Web of Science, and Cochrane Library) from January 2005 to February 2025 to identify published experimental and clinical studies. Given the emerging nature of VR technology applications in SCI-NP management and the relative paucity of high-quality evidence, this review adopted an inclusive approach to study selection. While prioritizing rigorously designed studies such as RCT and case-control studies, we also encompassed exploratory studies, feasibility studies, and pilot investigations to provide a thorough overview of the current research landscape and emerging trends in this domain. A comprehensive search was conducted by combining medical subject headings and free-text descriptors. The search descriptors included "virtual reality", "VR", "virtual walking", "spinal cord injury/spinal cord trauma", "neuropathic pain", "central pain", "neuralgia", "chronic pain", and "pain." The search strategy is as follows: (virtual reality OR VR OR virtual walking) AND (spinal cord injury OR spinal cord trauma) AND (neuropathic pain OR central pain OR neuralgia OR chronic pain OR pain).

Inclusion and Exclusion Criteria

The inclusion and exclusion standards were developed according to the Population-Concept-Context framework. Inclusion criteria comprised: (1) Population: Patients experiencing NP secondary to SCI; (2) Concept: Healthcare environments including hospitals, rehabilitation centers, and community-based facilities where VR interventions are delivered for therapeutic purposes; (3) Context: RCT, cohort studies, case-control studies, and observational clinical studies performed in healthcare environments. Exclusion criteria included: (1) Duplicate publications or conference abstracts; (2) Studies involving patients with NP not caused by SCI; (3) Investigations utilizing VR exclusively as an assessment tool rather than a therapeutic modality; (4) Studies with incomplete data or inadequately described methodologies.

Literature Screening and Data Extraction

The review methodology consisted of two phases: (1) title and abstract examination and (2) full-text assessment. Phase 1 involved importing retrieved literature into EndNote software, de-duplication screening, followed by independent screening of titles and abstracts by two researchers based on inclusion criteria, with cross-verification of screening results. Phase 2 involved full-text reading for secondary screening, recording reasons for exclusion with cross-verification of results. In case of disagreement, it was discussed and resolved with the 3rd researcher. Standardized data extraction was performed on the included literature after the screening of literature was completed, which included (1) authors, publication year, country of publication, study type, and study population; (2) interventions (including intervention device, form of intervention, and duration and frequency of intervention); and (3) outcome metrics and results of the interventions. Subsequently, we conducted a descriptive synthesis of the features and findings from the selected studies.

Quality Evaluation

As for quality assessment, we utilized the Joanna Briggs Institute (JBI) critical appraisal tools that permit the evaluation of the quality of studies for case reports, case series, observational studies, and randomized clinical trials.[18] The assessment criteria comprised 8–13 items, with the number of evaluated items varying according to study design. For each criterion, assessors provided ratings of "yes", "no", "unclear", or "not applicable." To evaluate the quality of included studies, two independent reviewers conducted the assessments; disagreements were resolved through consultation with a third reviewer.

Results

Literature Search

A systematic search of the three databases was conducted in strict accordance with predetermined inclusion and exclusion criteria. The initial search yielded 126 records. Following automated duplicate removal using EndNote 20 software (n=19) and additional manual screening for duplicates (n=2), 15 records were excluded due to unavailable full text. After comprehensive review of titles, abstracts, and full texts, studies not aligned with the research objectives were excluded, resulting in a final inclusion of 15 studies. The 15 included studies comprised 8 RCTs and 7 non-randomized studies, including clinical trials, feasibility studies, exploratory studies and pilot studies.

Regarding the methodological quality of the included studies, the primary methodological limitations were concentrated in two key areas: inadequate implementation of blinding procedures and incomplete follow-up protocols. Nevertheless, the majority of studies satisfied fundamental methodological quality criteria, thereby providing evidence-based support for the effectiveness of VR interventions.

The complete literature selection process is illustrated in Figure 1, while the baseline characteristics of included studies are presented in Table 1, and the quality assessment results are detailed in Table 2.

Application of VR in SCI-NP

Intervention Modalities and Content

VR technology can be categorized into three primary intervention modalities based on the degree of immersion: non-immersive VR, semi-immersive VR, and fully immersive VR.[34] Non-immersive VR systems utilize conventional devices such as personal computers, tablets, or smartphones, where users maintain some degree of connection with the physical environment during the experience. Semi-immersive VR systems employ large-scale display screens integrated with high-performance graphics processing units to create enhanced immersive virtual environments. Fully immersive VR systems typically utilize HMD that completely occlude users' visual perception of the external physical environment, enveloping their sensory systems within the virtual environment to achieve maximum immersive experience.

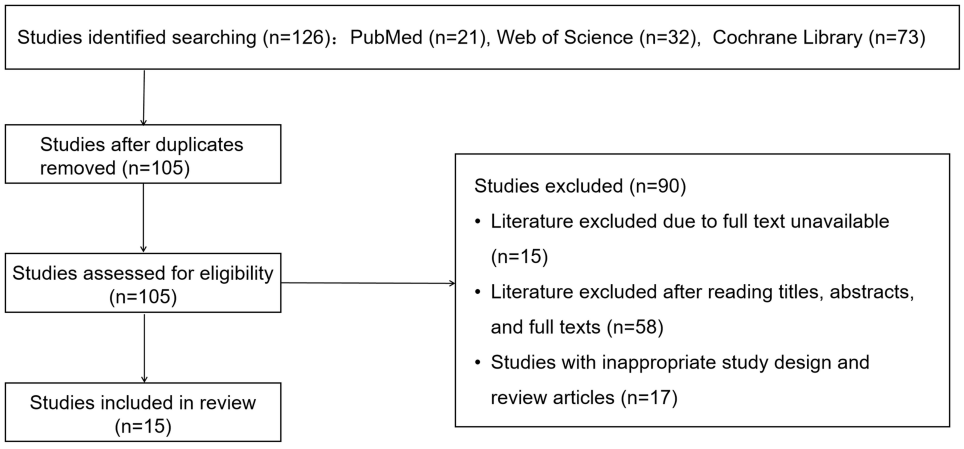

Figure 1 Flowchart of included studies.

Table 1 Characteristics and Outcomes of Included Studies

First Author	Year	Country	Type	Participants	Intervention	Frequency/ Duration	Outcome Measures	Results
Moseley[19]	2007	UK	Clinical Trial	5 SCI patients - Injury severity: AIS B - NLI: T/1, L/4 - Pain duration ≤ 4 years - DN4 ≥ 4	**2D Screen Intervention** - Virtual walking (actor's legs, patient's upper body) - Lead image - Animated comedy (placebo)	- 10 min/session - one time/day - 5 days/week - Lasts 3 weeks	VAS	**Post-training**: - Average pain reduction of 42 for virtual walking, 18 for guided imagery, and 4 for movie viewing (0–100 VAS) **At follow-up**: - Pain still relieved after 3 months of virtual walking
Soler[20]	2010	Spain	RCT	40 SCI patients - Injury severity: AIS A/8, B/32 - NLI: C3 and below - Injury time ≥ 1 year - Pain duration ≥ 6 months - NRS ≥ 4	**2D Screen Intervention** - Virtual walking (actor's legs, patient's upper body) - tDCS - Virtual walking + tDCS - Viewing images (placebo)	- 20 min/session - 5 days/week - Lasts 2 weeks	NRS NPSI BPI	**Post-training**: - The tDCS + Virtual walking group exhibited significant reductions in NRS, NPSI, and BPI scores, with significantly greater improvement compared to other groups - Anxiety self-ratings (NRS) were significantly reduced from baseline levels in all groups except the placebo group **At follow-up**: - tDCS + VR shows continued decrease in pain intensity; Single therapy did not show any improvement at 12-week follow-up
Villiger[21]	2013	Switzerland	Clinical Trial	14 SCI patients - Injury severity: AIS C/D - NLI: C4 and below - Injury time > 1 year	**2D Screen Intervention** - Foot and leg exercises using 4 VR movement exercises (foot leg sensors)	- 45 min/times - 4-5 times/week - Lasts 4 weeks	NRS	**Post-training**: - Pain intensity was reduced by 38.9% on average - Pain discomfort was reduced by 37.9% on average **At follow-up**: - At 12–16 weeks follow-up, the intensity of pain was reduced by 36.3% and the discomfort of pain was reduced by 29.6%
Özkul[22]	2015	Turkey	RCT	24 SCI patients - Injury severity: AIS A/17, B/4, C/3 - NLI: C/6, T/13, L/5 - Pain duration: 12.46 ± 17.83 months - VAS ≥ 4	**2D Screen Intervention** - 2 weeks VI + 2 weeks TENS - 2 weeks TENS + 2 weeks VI	VI: 15 min/day TENS: 30 min/day - 5 days/week - Duration 2 weeks	VAS NPS BPI	**Post-training**: - Between groups, the TENS group showed significantly greater improvement in maximum and minimum pain intensity, while the VI group demonstrated significantly better outcomes for pain sensory qualities, and Pain interference
Roosink[23]	2016	Canada	Exploratory study	9 SCI patients - Injury severity: AIS A/6, C/1, D/2 - NLI: C/3, T/5, L/1 - Injury time ≥ 3 months	**3D screen Intervention** - Interactive feedback (dynamic scenes + virtual characters) - Static feedback (only static scenarios)	- 12 sessions - interval ≥1 week	VAS	**Post-training**: - Pain intensity showed no significant change - Motor imagery (vividness/speed) significantly higher compared to a static virtual scene
Pozeg[24]	2017	Switzerland	RCT	20 paraplegic SCI patients and 20 healthy control participants - Injury severity: AIS A/15, B/3, C/2 - NLI: T2-L2 - Injury time ≥ 3.5 months	**3D VR headset** - Virtual leg illusion - Sensory illusion synchronous and asynchronous tactile stimuli corresponding to the virtual stimuli	- 2×2 repeated measure (60s)	VAS	**Post-training**: - Pain was significantly reduced only in the virtual leg illusion group when lower back stimulation was synchronized with virtual leg stimulation.

(*Continued*)

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Table 1 (Continued).

First Author	Year	Country	Type	Participants	Intervention	Frequency/ Duration	Outcome Measures	Results
Richardson[25]	2019	USA	RCT	59 SCI patients - Injury severity: AIS A/38, B/C/D 21 - Injury time ≥ 3 months	**3D Screen Intervention** - Virtual walking (First look) - Virtual wheelchair (First look)	- 20 min/session	NRS NPS	**Post-training**: - Participants in both groups experienced a reduction in pain, and there was no significant difference in pain changes between the two groups. - Virtual walking can significantly reduce the discomfort of NP, especially for "cold pain", "deep pain" and skin sensitivity.
Soler[26]	2021	Spain	RCT	130 SCI patients - Injury severity: AIS A/60, B/C/D 70 - NLI: C/45, T/85 - Injury time ≥ 6 months - NRS ≥ 4	**2D screen (virtual walking illusion)** - tDCS + visual illusion - Conventional therapy	- 30 min/day - 5 days/week - Duration 2 weeks	NPSI BPI PHQ-9	**Post-training**: - Compared with the control group, the experimental group reduced burning, pricking and touch-triggered pain, and improved depressive mood and sleep disorders
Austin[27]	2021	Australia	RCT	16 SCI patients - Injury severity: AIS A/10, B/2, C/1, D/3 - NLI: C6 and below - Injury time ≥ 6 months	**3D display versus 2D screen (natural scenery)** - 3D head-mounted VR reality - 2D screen display	- 15 min/session	NRS DASS IPQ	**Post-training**: - Pain intensity: pain was significantly reduced in 3D VR group - Emotion: no significant difference - Presence experience: the 3D VR group was significantly higher than the 2D group
Putrino[28]	2021	America	Pilot study	8 SCI patients - Injury severity: AIS B/2, C/3, D/3 - NLI: C/2, T/2, L/1 - Pain duration ≥ 6 months - Injury time:13 ± 4 years - NRS ≥ 4	**3D VR headset (first person view)** - Landscape environment: passive viewing of Natural scenery - Somatic environment: upper and lower limb movement scene	- 10 min/session	NRS ITQ PQ	**Post-training**: - NRS pain score was significantly reduced, but there was no significant difference between the two - The stronger the immersion tendency, the better the pain relief effect - There was no significant correlation between presence score and degree of pain reduction
Trost[29]	2022	America	Feasibility study	27 SCI patients - NLI: T / 24 - Injury time > 1 year - Pain duration > 3 months - NRS ≥ 4	**3D VR headset (first person view)** - Interactive virtual walking - Passive virtual walking	- < 30 min/time - 2 times/day - 5 days/week - Lasts 2 weeks	NRS NPS PANAS PHQ-9 PGIC	**Post-training**: - The intensity of pain, pain interference and NPS score in the interaction group decreased significantly, while the passive virtual walking group showed no significant changes - All participants showed a significant decrease in depressive symptoms and a significant increase in satisfaction **At follow-up**: No significant change
Mollà-Casanova[30]	2024	Spain	RCT	12 SCI patients - Injury severity: AIS C/D - Injury time > 1 year	**2D screen (virtual walking illusion)** - VI - TE	- 10 min virtual walking + 35 min TE - 3 days/week - Duration 6 weeks	BPI	**Post-training**: - Compared with the control group, the experimental group showed less pain and interference
Landmann[31]	2024	Switzerland	Feasibility study	4 SCI patients - Injury severity: AIS A/3, C/1 - NLI: T / 4 - Injury time ≥ 1 year - Pain duration ≥ 3 months - VAS ≥ 4	**2D screen (third person view)** - Virtual walking	- 2 times/week for 5 weeks - 5 times/week for 2 weeks	VAS PGIC DASS	**Post-training**: - Only one patient had improved pain intensity, depression, anxiety and stress, but all patients were highly satisfied with the treatment

Sabalette[32]	2024	Canada	Pilot study	4 SCI patients - Injury severity: AIS A/1, B/3 - NLI: C/4 - DN4 ≥ 4	- **3D VR headset** (Virtual walking from the first person perspective) - tDCS - Proprioceptive stimulation/MV 20 min of real or sham tDCS combined with three 10-min interventions: only MV, only VR, and (VR+MV)	- Once a week - Duration 4 weeks	NRS	**Post-training**: - Pain was significantly reduced after VR+MV intervention
Tabacof[33]	2024	America	RCT	22 SCI patients - Injury severity: AIS A/6, B/4, C/2, D/5, E/2, unavailable for 3 participants - Injury time ≥ 6 months - NLI: No restriction - Pain duration ≥ 6 months - NRS ≥ 2	**3D VR headset (first person view)** - Scenic VR environment - Somatic VR environment - Control (no video, only audio)	- 20 min/day - 3 days/week - Duration 4 weeks	NRS NPS NPSI PGIC	**Post-training**: - Compared to other groups, the Scenic group showed significant reductions in NPS and NPSI scores, the embodied group demonstrated significant improvements in NRS scores and patient global impression, while the control group showed no significant changes **At follow-up**: - The scenic group achieved significant decreases in NPSI, NRS, and NPS scores.

Abbreviations: NRCT, non-randomized controlled trial; RCT, randomized controlled trial; SCI, spinal cord injury; NP, neuropathic pain; VR, virtual reality; VI, visual illusions; TENS, transcutaneous electrical nerve stimulation; DN4, douleur neuropathique 4 Questions; VAS, visual analogue scale; NRS, numerical rating scale; BPI, brief pain inventory; tDCS, transcranial direct current stimulation; NPSI, neuropathic pain symptoms inventory; PHQ-9, Patient Health Questionnaire-9; DASS, Depression Anxiety and Stress Scale; IPQ, The Igroup Presence Questionnaire; ITQ, Immersive Tendencies Questionnaire; PQ, Presence Questionnaire; NPS, Neuropathic Pain Scale; PANAS, Positive and Negative Affective Scale; PGIC, Patients' Global Impression of Change; TE, therapeutic exercise; MV, muscle vibration.

Table 2 Quality Appraisal of Included Studies

Study	Quality Items												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Randomized Controlled Trial													
Soler[20]	Y	Y	Y	Y	Y	U	Y	Y	Y	Y	Y	Y	Y
Özkul[22]	Y	U	Y	U	U	U	Y	N	U	Y	Y	Y	Y
Pozeg[24]	Y	U	Y	N	N	U	Y	Y	Y	Y	Y	Y	Y
Richardson[25]	Y	Y	Y	Y	N	Y	N	N	N	Y	Y	Y	Y
Soler[26]	Y	U	Y	U	Y	U	N	N	Y	Y	Y	Y	Y
Austin[27]	Y	Y	Y	N	N	U	N	U	U	Y	Y	Y	Y
Mollà-Casanova[30]	Y	Y	Y	Y	Y	U	Y	N	U	Y	Y	Y	Y
Tabacof[33]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Quasi-Experimental Studies													
Moseley[19]	Y	Y	Y	N	U	Y	Y	Y	Y	_	_	_	_
Villiger[21]	Y	Y	U	N	Y	Y	Y	Y	Y	_	_	_	_
Roosink[23]	Y	Y	N	N	Y	N	Y	Y	Y	_	_	_	_
Putrino[28]	Y	N	N	N	Y	N	Y	Y	Y	_	_	_	_
Trost[29]	Y	Y	U	Y	Y	Y	Y	Y	Y	_	_	_	_
Landmann[31]	Y	Y	U	N	Y	N	Y	Y	N	_	_	_	_
Sabalette[32]	Y	Y	Y	N	Y	N	Y	Y	N	_	_	_	_

Abbreviations: Y, yes, clear report; N, no, not reported; U, unclear; "-", not applicable.

Among the 15 included studies, eight employed semi-immersive 2D screen-based interventions,[19–22,26,30,31,33] six utilized immersive 3D interventions,[23–25,28,29,32] and one investigation incorporated both modalities to compare their respective therapeutic efficacies.[27]

Regarding specific intervention modalities, VR-guided visual illusion interventions and landscape-based interventions were predominantly employed. Visual illusion interventions enabled patients to perceive leg movement through virtual walking experiences. One recent investigation incorporated VR-assisted interactive virtual ambulation interventions.[29] Several studies implemented combined therapeutic approaches, integrating VR with complementary treatment modalities including tDCS[20,26] (two studies), tactile stimulation[24] (one study), exercise therapy[21,30] (two studies), and proprioceptive stimulation/muscle vibration[32](one study). Control interventions primarily comprised virtual wheelchair experiences, conventional treatment protocols, or placebo interventions, with placebo conditions including animated comedy viewing, image observation, and sound-only exposure.

Outcome Measures and Assessment

Outcome measures for VR treatment of SCI-NP encompassed three primary domains: pain assessment, emotional evaluation, and intervention quality metrics.

Pain Assessment: Pain-related outcomes included pain intensity, pain characteristics, and pain interference. Pain intensity was evaluated using the Visual Analogue Scale (VAS), Numerical Rating Scale (NRS), while the Brief Pain Inventory (BPI) also incorporates pain intensity ratings. Neuropathic pain diagnosis and pain characteristics were assessed through the Neuropathic Pain Scale (NPS) and Neuropathic Pain Symptoms Inventory (NPSI), evaluating five dimensions: superficial spontaneous ongoing pain, deep spontaneous ongoing pain, paroxysmal pain, evoked pain,

and hypoesthesia. Pain descriptors encompassed qualitative characteristics including sharp, burning, dull, cold, itching, deep, and superficial pain sensations. Pain interference is measured using the BPI, which evaluates pain's impact across seven domains: daily activities, mood, walking ability, work performance, interpersonal relationships, sleep quality, and enjoyment of life. The NRS score can also be used to assess pain's impact on daily functioning.

Emotional Assessment: Patient psychological status was evaluated using standardized instruments including the Patient Health Questionnaire-9 (PHQ-9), Positive and Negative Affect Schedule (PANAS) and Depression Anxiety Stress Scales (DASS).

Intervention Quality: Treatment quality was primarily assessed through the Patient Global Impression of Change (PGIC) to capture overall treatment response, while the Igroup Presence Questionnaire (IPQ), Immersive Tendencies Questionnaire (ITQ) and related presence questionnaires measured patients' sense of presence and immersion within the virtual environment.

Effectiveness of VR Treatment for SCI-NP

The therapeutic effectiveness of VR interventions for SCI-NP encompasses multiple outcome domains including pain intensity, pain characteristics, pain interference, emotional status, and intervention quality. Figure 2 illustrates the overall improvement rates across multiple domains and the improvement rates associated with different VR application modalities.

Pain Intensity: Among the 15 studies included in this review, all except Soler et al,[26] examined pain intensity outcomes, with 12 studies demonstrating varying degrees of analgesic effects from VR interventions, While two studies failing to show significant analgesic effects.[22,23] Seven studies[19,25,27–29,31,33] demonstrated that standalone VR interventions, including virtual walking and immersive virtual environments, significantly improved pain intensity in SCI-NP patients. Five studies[20,21,24,30,32] reported significant analgesic efficacy for combined VR interventions, encompassing VR with tDCS, VR with exercise therapy, VR with tactile stimulation, and VR with proprioceptive stimulation/muscle vibration. However, in VR combined with tactile stimulation interventions, significant pain reduction occurred only when tactile stimulation was temporally synchronized with virtual leg movements.[24]

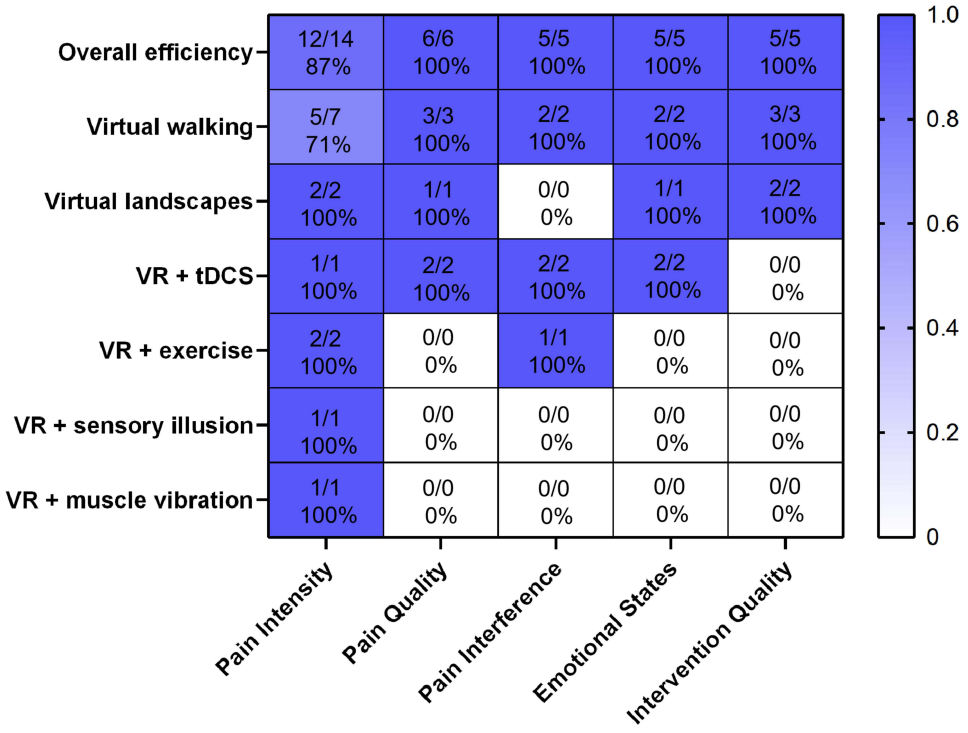

Figure 2 Application Effect Heatmap.

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Pain Characteristics: Six studies investigated VR effects on pain quality and characteristics.[20,22,25,26,29,33] Two studies[22,25] demonstrated that virtual walking interventions provided superior improvements in burning sensations, sharp pain, deep pain, cold pain, and skin hypersensitivity compared to transcutaneous electrical nerve stimulation and virtual wheelchair controls. Building upon these findings, Trost et al[29] compared passive versus interactive virtual walking interventions, revealing that the interactive virtual walking group achieved significantly greater overall improvements in pain quality, though specific domains were not specified. Soler et al[20] compared four intervention conditions: virtual walking alone, tDCS alone, their combination, and placebo. Results showed that virtual walking alone significantly improved ongoing pain and dysesthesia, while the combined intervention with tDCS enhanced ongoing pain, paroxysmal pain, allodynia and dysesthesia with superior efficacy. The team's subsequent research similarly demonstrated that combined virtual walking and tDCS provided greater advantages in pain quality improvement compared to standard care, including reductions in burning sensations, stabbing pain, and allodynia.[26] These findings collectively underscore the significant role of virtual walking interventions in pain quality improvement, whether implemented as standalone or combined approaches. Conversely, Tabacof 's[33] recent study showed that virtual landscape interventions produced more significant pain quality improvements compared to virtual walking interventions or no treatment controls. While this finding differs from previous results, it reinforces the overall therapeutic effects of VR interventions.

Pain Interference: Five studies[20,22,26,29,30] examined pain interference outcomes, including the aforementioned research by Trost[29] and Soler et al[20,26] Results were consistent, demonstrating that interventions more effective for pain quality improvement also provided superior pain interference relief. Soler 's two studies revealed that combined interventions offered greater benefits across multiple domains: mood, daily activities, work performance, sleep quality, enjoyment of life, functional capacity, and interpersonal relationships.[20,26] Trost et al[29] demonstrated that interactive virtual walking interventions significantly reduced pain's overall interference with daily activities. Additionally, studies by Okzul[22] and Mollà-Casanova[30] showed that virtual walking interventions, both alone and combined with exercise therapy, significantly improved functional capacity in SCI-NP patients compared to transcutaneous electrical nerve stimulation and placebo controls. These five studies collectively demonstrated notable VR effects on mood, sleep, and functional outcomes,[20,22,26,29,30] with at least two studies showing positive effects on mood and sleep,[20,26] and three studies effectively enhancing patients' functional capacity.[20,22,30]

Emotional Status: Five studies evaluated VR effects on psychological outcomes in SCI-NP patients, specifically examining depression and anxiety symptoms.[20,26,27,29,31] One feasibility study demonstrated that virtual walking interventions provided benefits for both anxiety and depression.[31] Austin et al[27] found similar dual benefits, observed in both the experimental group (3D virtual landscape intervention) and control group (2D virtual landscape intervention). A second feasibility study showed significant improvements in patient anxiety with virtual walking interventions, with no significant differences between interactive and passive approaches.[29] Another RCT yielded comparable results, showing that both standalone and combined interventions reduced anxiety symptoms without significant between-group differences.[20] Soler et al's[26] recent study revealed significant between-group differences, with combined interventions producing superior improvements in depressive symptoms compared to standard care. Despite varying methodological approaches, these findings consistently demonstrated VR's beneficial effects on patient emotional states: two studies showed improvements in both anxiety and depression,[27,31] two studies demonstrated significant anxiety reduction,[20,29] and one study revealed significant depression improvement.[26]

Intervention Quality: Five studies examined intervention quality outcomes.[27–29,31,33] Three studies reported patient global impression of change, with Landmann[31] and Tabacof[33] showing higher patient self-rated overall improvement scores following virtual walking interventions. Trost et al[29] demonstrated similar results without significant between-group differences. Two studies examining presence and immersion found that 3D VR interventions, including virtual landscapes and virtual walking, enhanced patients' sense of presence.[27,28] One investigation additionally demonstrated increased immersion levels, noting that greater immersive propensity was associated with superior analgesic outcomes in virtual environment interventions.[28]

Discussion

This review identified 15 studies, comprising 8 RCTs, 2 clinical trials, 2 pilot studies, 2 feasibility studies, and 1exploratory study, encompassing more than 400 SCI-NP patients. Through analysis of the respective study findings, we discuss the efficacy, underlying mechanisms, and future directions of VR technology in SCI-NP treatment.

Effectiveness Analysis of VR in SCI-NP Treatment

Although promising trends were observed in the included literature, particularly regarding short-term SCI-NP relief, standardized research approaches remain lacking. Previous studies have indicated that intervention modalities, specific intervention form, intervention duration, and participant characteristics may influence treatment outcomes, yet systematic investigations have not been conducted.

Intervention modalities encompass different equipment types and viewing perspectives. Previous research has demonstrated that presence and immersion are key determinants of VR treatment efficacy, with higher degrees of immersion and presence being directly correlated with superior pain relief outcomes.[29] Variations in intervention equipment and viewing perspectives constitute important factors influencing these parameters,[27] with 3D, interactive devices and first-person perspective interventions typically generating greater immersion and enhancing therapeutic effects. Austin et al[27] conducted a randomized controlled study comparing 3D head-mounted display-based VR interventions versus 2D screen-based VR interventions for SCI-NP patients, demonstrating that 3D interventions resulted in significant reductions in pain intensity and significant improvements in sense of presence compared to 2D interventions. Trost et al[29] examined the effects of passive versus interactive virtual walking interventions using 3D technology, finding that the interactive group achieved significantly greater reductions in pain intensity, pain interference, and NPS scores compared to the passive group, though this was not a randomized controlled study. Furthermore, no studies have systematically compared the effects of different viewing perspectives, necessitating future high-quality RCTs for further validation.

VR interventions are primarily categorized into two types: standalone and combined approaches. This review included nine studies examining standalone VR interventions, encompassing both virtual walking and virtual landscape interventions.[19,22,23,25,27–29,31,33] Two studies compared the therapeutic efficacy of these approaches, Putrino et al[28] found that both interventions significantly reduced NRS pain scores post-intervention, with no significant between-group differences. Another study revealed that while virtual walking interventions provided significant short-term analgesic effects, virtual landscape interventions were more effective in improving pain quality.[33] These findings suggest that both intervention modalities are essential, as they address different dimensions of pain management needs. Future research and clinical practice may leverage their respective advantages based on specific clinical contexts. All six studies[20,21,24,26,30,32] examining combined VR interventions in this review demonstrated significant analgesic efficacy, including VR combined with tDCS,[20,26] exercise therapy,[21,30] tactile stimulation,[24] and proprioceptive stimulation/muscle vibration.[32] One study employed a randomized controlled design to compare standalone VR intervention with VR combined with tDCS, showing that the combined approach produced significantly greater improvements in pain intensity and pain interference, with effects sustained through 12-week follow-up.[20] Another study compared VR combined with tDCS to standard care, finding superior effectiveness of the combined intervention across pain quality, pain interference, and emotional state outcomes.[26] Mollà-Casanova et al[30] conducted a RCT comparing virtual walking combined with exercise therapy versus placebo combined with exercise therapy, demonstrating greater improvements in pain intensity and pain interference with the virtual walking combination in SCI-NP patients. Other combined intervention studies did not compare against standalone VR interventions or standard care, and while showing certain advantages, lack evidence of superiority over standalone VR interventions or conventional treatments.

Research by Laver et al on VR treatment in stroke patients demonstrated that appropriately extending individual session duration and increasing total intervention periods may more effectively promote neuroplasticity changes,[35] thereby alleviating pain. However, no studies have systematically examined the temporal effects of VR in SCI-NP treatment. Although Landmann et al[31] considered the influence of timing and frequency factors, they only investigated variations in timing and frequency while maintaining consistent total session numbers, specifically comparing twice

weekly for five weeks versus five times weekly for two weeks, without conducting more comprehensive temporal factor analyses. Future research requires more systematic investigations to determine and standardize optimal parameters.

Regarding participant characteristics, whether injury severity and lesion level influence treatment outcomes remains unclear. Research by Moseley et al[19] indicated that participant injury severity and lesion level may represent the most important and reliable predictors of virtual walking success, with their findings indicating that patients with incomplete thoracolumbar spinal cord injuries demonstrate greater therapeutic benefits from virtual walking treatments. Virtual walking interventions primarily provide a visual illusion of lower limb movement,[36] which may theoretically be more effective for SCI patients experiencing lower limb NP—a condition commonly observed in thoracolumbar SCI patients. While providing attentional distraction, these interventions help restore visual-proprioceptive coherence in the lower limbs,[36] enhance functional connectivity between primary somatosensory (S1) and primary motor (M1) cortical areas,[37] and modulate neuroplasticity changes to achieve pain relief. Additionally, the superior outcomes in incomplete injuries may be attributed to preserved sensorimotor pathways, as retained neural circuits support neuroplasticity in both brain and spinal cord, facilitating the establishment of new neural connections and thereby modulating pain signals.[38,39] However, it is important to note that these conclusions are not derived from large-scale RCTs. Therefore, whether patient characteristics influence the effectiveness of virtual walking and other VR interventions, particularly their specific effects on SCI-NP, requires validation through additional high-quality prospective studies.

In addition to the aforementioned issues, the long-term efficacy of VR for SCI-NP relief remains controversial. From a neural remodeling perspective, the chronicity of SCI-NP fundamentally stems from aberrant central nervous system plasticity, with processes such as synaptic remodeling and cortical representational reorganization requiring extended periods to achieve stability.[40] Notably, VR interventions exert their long-term therapeutic effects precisely through the correction of aberrant sensorimotor integration and the gradual induction of cortical functional reorganization.[16] This neuroplasticity-based mechanism of action inherently necessitates sustained intervention over extended periods for gradual manifestation. The majority of interventions in this review were predominantly 2 weeks in duration, with the longest intervention period being 6 weeks,[30] however, the longest one did not include follow-up evaluations at two weeks or beyond, thereby limiting validation of VR's long-term efficacy. Among the five studies incorporating follow-up evaluations, interventions by Moseley,[19] Villiger,[21] and Tabacof[33] exceeded three weeks in duration, while those by Soler[20] and Trost[29] lasted two weeks. All five studies employed virtual walking interventions. Results demonstrated that Moseley[19] and Villiger[21] continued to observe pain intensity reductions following three-month interventions, whereas Soler[20] and Trost[29] detected no sustained analgesic effects following two-week interventions. However, Tabacof,[33] despite similarly implementing interventions exceeding three weeks, found no sustained pain relief effects, presenting conflicting evidence. Therefore, future systematic investigation remains necessary to clarify VR's long-term therapeutic efficacy for NP management.

In addition to VR's potential for improving SCI-NP pain-related symptoms, the data also support VR's beneficial effects on quality of life and emotional well-being. Regarding quality of life, VR demonstrates significant efficacy in improving mobility, activities of daily living, sleep quality, and anxiety and depression symptoms.[20,22,26,29,30] Concerning emotional outcomes, controlled trials comparing VR with standard interventions showed significant improvements in VR groups.[26] However, in controlled trials examining specific VR intervention modalities—such as comparing 3D displays versus 2D screens,[27] interactive virtual walking versus passive virtual ambulation,[29] and single versus combined VR interventions[20]—both experimental and control groups demonstrated improvements with no significant between-group differences. This suggests that VR's emotional benefits may be independent of specific intervention formats, with all forms of VR interventions demonstrating efficacy. The benefits identified in this review support future research endeavors to further elucidate VR's potential impact on quality of life and emotional well-being.

Mechanisms of Action of VR Treatment for SCI-NP

VR technology delivers visual, auditory, tactile, and interactive feedback through various display devices and advanced motion tracking systems. This multisensory intervention not only effectively diverts patients' attention from pain but also facilitates the modulation of aberrant pain networks, promotes cortical reorganization, and ameliorates abnormal central pain processing mechanisms, thereby alleviating the pain experience.[40,41]

VR may redirects patients' attention from pain perception to virtual tasks through highly immersive virtual environments. According to Melzack and Wall's[42] gate control theory of pain, when the brain concentrates on processing virtual environment information, pain signal transmission becomes inhibited. Specifically, the somatosensory and motor stimulation provided by virtual environments can activate large-diameter Aα and Aβ fibers, which compete with small-diameter Aδ and C fibers (pain-conducting fibers) for processing resources at the spinal and thalamic levels. This competition inhibits or attenuates pain signal transmission, reducing pain processing capacity and consequently alleviating pain.[41] This attention-diversion mechanism plays a crucial role in pain relief. Research by Bantick et al[43] demonstrated that when healthy participants were distracted during painful thermal stimulation, pain intensity decreased. Concurrently, functional imaging using functional magnetic resonance imaging (fMRI) revealed reduced activation in the thalamus, insula, and cognitive anterior cingulate cortex (ACC), along with increased deactivation in the emotional ACC and orbitofrontal cortex. Additionally, increased activity in the periaqueductal gray (PAG) and posterior thalamus was observed.[44] The PAG represents a critical component of the descending pain inhibitory system, playing a pivotal role in descending pain modulatory pathways and analgesia.[45] It serves as a convergence site for multiple higher-order pain centers projecting to the brainstem, transmitting inhibitory signals to the spinal cord and promoting opioid release,[46] thereby reducing central sensitization and achieving pain modulation. However, most studies included in this review lack analytical validation based on functional brain imaging and neuroimaging results, which limits both the persuasiveness of their findings and our understanding of the neural mechanisms underlying VR treatment for SCI-NP.

SCI induces plasticity alterations in the S1 and M1. These manifestations include: reduced S1 gray matter volume,[47] which exhibits a negative correlation with pain severity. The reduction in gray matter volume might reflect decreased neuronal dendritic complexity and diminished synaptic connections, thereby compromising normal sensory information processing. Additionally, M1 activity becomes diminished,[48] with decreased M1 activity resulting in weakened regulation of the descending pain inhibitory system, facilitating pain signal transmission to higher cortical centers. The M1 is intimately connected to the PAG-rostral ventromedial medulla (RVM)-spinal dorsal horn (SDH) descending pain inhibitory pathway, where M1 stimulation enhances ipsilateral PAG neuronal firing activity while reducing GABAergic interneuron inhibition of PAG projection neurons, thereby activating the descending pain inhibitory pathway.[49] This activation promotes endogenous opioid release, effectively suppressing pain signal transmission and ultimately reducing pain perception; however, this mechanism becomes compromised following SCI.[50] Furthermore, S1-M1 functional connectivity undergoes alterations, with resting-state functional connectivity (rsFC) studies demonstrating that SCI results in weakened functional connectivity between S1 and M1 regions, while connectivity with other pain-related brain areas (insula, ACC) becomes enhanced.[51] This aberrant connectivity pattern facilitates pain network activation,[51] thereby inducing NP. A comprehensive consequence of the aforementioned structural and functional alterations is the induction of sensorimotor integration circuit dysfunction, resulting in discrepancies between visual feedback and proprioceptive input, which trigger and exacerbate pain. Another core mechanism underlying VR treatment of SCI-NP involves correcting the mismatch between cortical motor output and sensory feedback through multisensory integration and motor imagery, thereby inducing cortical functional reorganization.[16] This effect is particularly pronounced in virtual walking interventions, which involve immersive VR environments designed to enhance participants' motor imagery capabilities for walking. Malouin et al[52] reported activation of the M1 during motor imagery tasks. Research by Diers et al[37] demonstrated that providing visual feedback congruent with anticipated movement during motor imagery simultaneously activates both S1 and M1 regions while enhancing functional connectivity between these areas. This enhanced functional connectivity may facilitate restoration of disrupted sensorimotor circuits and reconstruction of mismatched afferent-efferent feedback loops, thereby alleviating pain. Concurrently, M1 activation effectively engages the endogenous descending pain inhibitory system through the release of inhibitory neurotransmitters such as endorphins and norepinephrine, reducing central sensitization and inhibiting nociceptive transmission at the spinal level.[49] However, this neuroplasticity-based mechanism inherently requires sustained intervention over extended periods for gradual manifestation. Therefore, while VR interventions may produce immediate analgesic effects through attention-diversion mechanisms in the short term, achieving persistent therapeutic benefits based on neuroplasticity necessitates prolonged continuous intervention.

Conclusion

This scoping review integrates existing evidence on VR therapy for SCI-NP by constructing a multidimensional assessment framework through synthesis of 15 empirical studies. In contrast to previous reviews that focused solely on research paradigms examining pain intensity indicators, this review innovatively expands the assessment dimensions to encompass key domains including pain characteristics, pain interference, emotional status, and intervention quality, thereby further elucidating the multifaceted therapeutic potential of VR for SCI-NP. We examined the emerging patterns of VR utilization in NP patients, with results demonstrating that VR technology exhibits short-term therapeutic potential for pain relief and emotional improvement. However, while VR technology demonstrates therapeutic benefits, the current evidence base has not established its superiority over conventional treatment modalities, thus remaining insufficient to support VR as a standalone clinical therapeutic intervention.

The primary limitations of the current evidence are manifested in several key areas: First, although most studies confirmed VR's therapeutic efficacy, only one investigation employed a rigorous RCT design to directly demonstrate VR's superiority over conventional treatment in pain management and emotional improvement. The remaining studies predominantly utilized pre-post comparisons or placebo-controlled designs, lacking direct comparisons with standard care protocols. This methodological approach can only establish that VR is effective rather than demonstrating superior efficacy, leaving uncertainty regarding whether VR can match or exceed current standard treatment protocols. Second, substantial heterogeneity exists across studies in critical methodological parameters, including VR device configurations (immersive versus non-immersive interventions), intervention content (virtual walking versus virtual environment experiences), delivery modalities (standalone versus combination therapies), and treatment frequency and duration. This heterogeneity not only impedes the identification of optimal intervention protocols but also precludes the provision of clear clinical implementation guidelines. Third, existing studies employ incomplete evaluation frameworks. Given that SCI-NP impacts patients across physiological, psychological, and social functional domains, therapeutic assessment should encompass multidimensional indicators including pain intensity, pain characteristics, functional interference, and psychological status to establish comprehensive evaluation systems. However, most current studies focus exclusively on single or limited outcome measures, failing to capture the full spectrum of VR intervention effects. Future research endeavors should focus on elucidating the precise neurophysiological mechanisms underlying VR interventions through advanced techniques such as functional neuroimaging; conducting high-quality RCTs to determine optimal intervention parameters (including device specifications, intervention frequency, and duration) and target populations; and developing comprehensive multidimensional assessment frameworks encompassing pain, functional, and psychological outcomes to maximize the clinical utility of VR in NP management.

While existing literature provides preliminary evidence for the efficacy of VR interventions in treating SCI-NP, several limitations may challenge widespread clinical implementation. From an implementation feasibility perspective, VR interventions require substantial initial investment, encompassing hardware components (head-mounted displays, tracking systems, computing equipment), software development or licensing fees, and staff training costs. Despite higher upfront costs compared to conventional pharmacological and physical therapies, VR technology demonstrates favorable long-term cost-effectiveness potential, as single equipment investments can serve multiple patients, reduce dependence on specialized therapists, and enable home-based treatment delivery. Patient acceptability also influences implementation success, with future VR deployment requiring consideration of cognitive functional capacity, age-related technology adoption barriers, and cultural variations to enhance clinical applicability.

Based on these limitations, VR technology should be positioned as an effective adjunct to, rather than a replacement for, conventional treatments. By integrating VR with established therapeutic approaches such as exercise interventions, physical therapy, or psychological interventions, a multimodal comprehensive treatment framework can be developed that leverages the unique advantages of VR while ensuring patients receive evidence-based standard care, ultimately achieving synergistic therapeutic effects while maintaining treatment safety and efficacy.

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