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# A scoping review on the role of virtual walking intervention in enhancing wellness



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Virtual walking has the potential to be an adjunct to traditional physical therapy. This scoping review aims to synthesize evidence on the characteristics, effectiveness, feasibility, and neurological mechanism of virtual walking interventions on health-related outcomes. Articles in English were retrieved from twelve databases (January 2014–October 2024). Thirteen interventional studies were included, focusing on three types of virtual walking: passive observing moving (71.4%), arm swing locomotion (21.5%), and foot tracking locomotion (7.1%). Most studies (84.6%) involved individuals with spinal cord injuries, while the remaining studies focused on lower back pain (7.7%) and lower limb pain (7.7%). Over 70% of studies lasted 11–20 min, 1–5 weekly sessions for 10–14 days. Statistically significant findings included pain reduction (84.6%), improved physical function (mobility and muscle strength), and reduced depression. Mild adverse effects (fatigue and dizziness) were transient. Neurological evidence indicates somatosensory cortex activation during virtual walking, possibly linked to neuropathic pain.

Virtual walking interventions have emerged as innovative rehabilitation methods for individuals with mobility disabilities[1,2]. Virtual walking refers to the experience of individuals walking in a non- to fully immersive virtual environment while stationary in the physical environment[3]. Exercise for mobility disabilities improves fitness, physical function, and emotional health[4,5]. Despite evidence that supports the benefits of traditional exercise, it can be problematic for people with mobility impairments. Non-clinical environments often lack accessible facilities and trained staff, making it difficult for them to exercise. Additionally, they may feel bored with conventional arm exercise equipment[6,7]. Virtual walking is a potential cost-effective therapeutic tool that can overcome this barrier. Furthermore, studies suggested that the virtual walking technique is superior in providing sensory feedback, intuitive navigation, and cognitive demands[8,9]. Virtual walking may activate the somatosensory cortex by reinstating sensory input through visual illusion, potentially modulating brain functional reorganization associated with deafferentation-induced neuropathic pain[10].

A variety of virtual walking techniques have been proposed[11]. The earlier virtual walking methods adopted visual illusions, allowing patients to view projected virtual walking legs combined with their real bodies reflected in a mirror, which demonstrated a positive effect on pain[12]. A 2014 narrative review on virtual feedback included five articles that used walking observation interventions on people with spinal cord injury (SCI), showing a reduction in pain intensity[13]. However, one recent randomized controlled trial (RCT) for individuals with SCI yielded contradictory findings, as no significant change in pain intensity was observed between groups; however, physical functions such as muscle strength and walking performance improved in the virtual walking group[1]. Similarly, a 2017 study explored the use of computers to combine live images of participants and walking legs, with 69.5% of participants significantly improving their average pain levels[14]. More recent advancements in virtual walking interventions incorporate head-mounted devices (HMDs) with multiple sensory inputs, including sound, head and body tracking sensors, and additional input devices like joysticks and data gloves[15]. For example, a study employed hand controllers to track the arm swings of participants with SCI and transform them into leg movements, allowing participants to view their virtual arms and legs through an HMD. The results showed significant improvements in neuropathic pain (effect size *(ES)* = 0.31), mood and affect (*ES* = −0.16), and depression (*ES* = 0.13)[16]. However, a subsequent pre-post quasi-experiment study using the same intervention reported a significant decrease in pain intensity but no significant change in pain-related disability or pain

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interference[17]. In summary, cumulative trials are characterized by diverse virtual walking methods with mixed and often controversial results. This highlights the pressing need for a scoping review that encompasses all virtual walking modalities to refine the standardizing protocols.

Despite the increasing use of virtual walking interventions, there has yet to be a dedicated review specifically focused on these interventions. A 2021 scoping review examined virtual reality (VR) for managing neuropathic pain in individuals with SCI, including nine studies utilizing virtual walking or limb movement imagery. However, this review did not focus exclusively on virtual walking interventions, and while eight of the included studies reported significant pain reductions, the overall quality of evidence was low[18]. A subsequent 2024 systematic review expanded the scope to include 46 studies on VR-based rehabilitation for SCI, reporting outcomes related to lower limb mobility, gait, and pain. However, this review lacked both detailed categorization of VR interventions and sufficient RCTs to adequately strengthen its conclusions[19]. Emerging research suggests that virtual walking may improve not only pain but also physical function, psychological well-being, and underlying neurological mechanisms. Therefore, this scoping review will address the identified gaps by narrowing its focus specifically to virtual walking interventions and systematically mapping the available evidence.

This scoping review aims to 1) synthesize the characteristics of virtual walking interventions, 2) synthesize evidence of the effectiveness, feasibility, and acceptability, and 3) explore potential neurological mechanisms on health-related outcomes.

## Results

### Study selection, study characteristics, participant characteristics

Figure 1 depicts the study selection process via a PRISMA flow diagram. A total of 3882 articles were identified through searching the specified database and manual searches of the reference lists. After removing 1323 duplicates and screening 2549 titles and abstracts, 141 articles remained. After a full-text review, 13 clinical trials met the inclusion criteria as detailed in Table 1[1,2,14,16,17,20–27].

Five types of research designs were used: a group pre-post study (35.8% of the studies)[14,17,21,25,26], an RCT (28.6% of the studies)[1,23,24,27], a controlled experimental study (21.4% of the studies)[2,14,16], a feasibility study (7.1%)[22], and a pilot experimental study (7.1%)[20]. More than half of the studies were carried out in hospitals, rehabilitation centers, or clinics (69.2%)[1,2,14,20–24,27], and 23.1% of the studies permitted participants to engage in virtual walking at home ($n = 3$)[16,17,26]. The studies were mainly published in the USA ($n = 4$)[17,20,21,24] and Spain ($n = 3$)[1,2,14], followed by Turkey ($n = 2$)[23,27] and Switzerland ($n = 2$)[22,26], with two studies undertaken in Canada[25] and Australia[16], respectively. These studies were published mainly between 2015 and 2021.

A total of 439 participants were included, with ages ranging from 29 ± 3.6 to 60 ± 10.2 years. The participants were categorized into two main groups: those with SCI (84.6%)[1,2,16,17,20–26], and those with pain conditions (lower back pain (7.7%)[27], and lower limb neuropathic pain (7.7%))[14]. The mobility abilities of the participants were consistent with their conditions, as individuals with SCI used wheelchairs for locomotion (84.6%), while the remaining participants were able to walk normally.

### Intervention characteristics

As shown in Table 2, the intervention content included virtual walking only or a combination of virtual walking with rehabilitation therapies. The rehabilitation therapies included Transcranial Direct Current Stimulation (tDCS) ($n = 2$)[2,14], Transcutaneous Electrical Nerve Stimulation (TENS) ($n = 1$)[23], and therapeutic exercise ($n = 1$)[1]. For the control group, six studies used an active control group, including observing virtual walking ($n = 4$)[1,16,20,24], traditional physical therapy ($n = 1$)[27], and TENS ($n = 1$)[23]. One study employed inactive control, focusing on monitoring the stability of pain measurement[2].

The virtual walking modality included virtual illusion ($n = 9$, 64.3%, one article has both illusion and avatar)[1,2,14,20–22,24,25,27] and virtual avatar ($n = 5$, 35.7%)[16,17,23,25,26]. The virtual walking locomotions were categorized into three different types: ten focused on passive observing moving (71.4%)[1,2,14,20–25,27], three on arm swing locomotion (21.4%) (one study also included passive observation)[14,16,17], and one on foot tracking locomotion

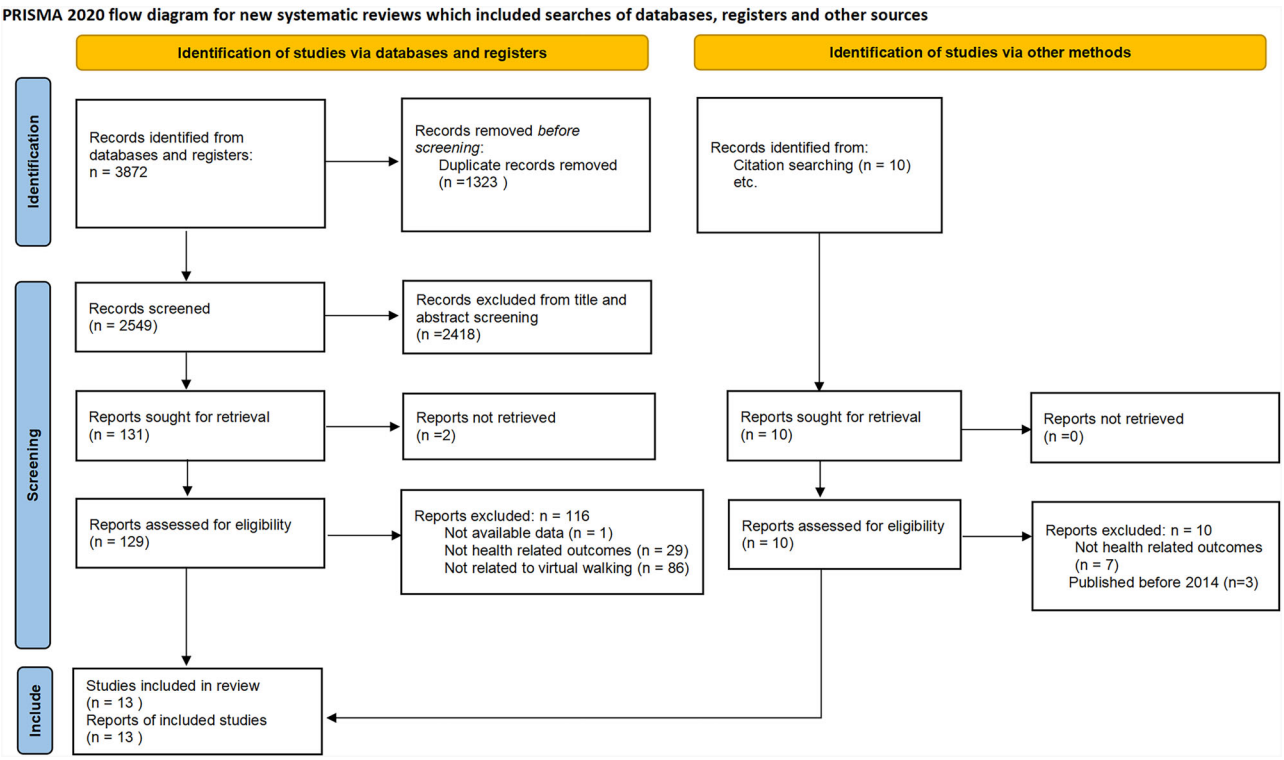


**Fig. 1 | PRISMA 2020 flow diagram.** The flow diagram illustrates the identification, screening and including process of studies. *n* represents the number of studies.

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**Table 1 | Overview of Study Design, Population, Health Outcomes, and Feasibility of Virtual Walking Interventions**

| Study characteristics | | | Outcomes and findings | | |
|---|---|---|---|---|---|
| **Author, Year; Country** | **Study design; Sample size; Setting** | **Population (Disease, Age (Mean (SD) years), Mobility)** | **Health-related outcomes** | **Neurological mechanism** | **Feasibility and acceptability** |
| (Eick et al.[20]); USA; | Pilot experiment;<br>I: $n = 3$,<br>C: $n = 5$;<br>Rehabilitation Clinic | Paraplegia/Able-bodied;<br>I: 29.0 (3.6),<br>C: 31.6 (7.8);<br>Wheelchair | NR | • Cerebral blood flow (fMRI): During VW process, an activation in the bilateral somatosensory cortex and paracentral lobule in paraplegia patient[a] | Recruitment: NR;<br>Adherence: 100%;<br>Satisfaction: NR;<br>Drop-out: 0 |
| (Mollà-Casanova et al.[1]); Spain | Pilot randomized control trial;<br>I: $n = 6$,<br>C: $n = 6$;<br>Hospital | Incomplete spinal cord injury;<br>Total: 52.0 (14.7);<br>Wheelchair | • Neuropathic Pain (Brief Pain Inventory): After intervention, no significant change in pain severity and interference in both groups;<br>• Physical Function: 1) Muscle Strength: After intervention, improvements in tibialis anterior mean strength[a] (95% $CI = -56.29$ to $-2.02$, Cohen's $d = -0.51$) and maximum strength in intervention group[a] (95% $CI = -60.67$ to $-2.90$, Cohen's $d = -0.18$). 2) Walking Performance: After intervention, walking speed improved[a] (95% $CI = 0.90$ to 6.00, Cohen's $d = 0.52$) in the 10-Meter Walk Test, walking ability improved[a] (95% $CI = -2.51$ to $-0.159$, Cohen's $d = 0.13$) in the Walking Index for Spinal Cord Injury in intervention group | NR | Recruitment: 80%<br>Adherence: All participants completed 80% of intervention;<br>Satisfaction: 91.67% of participants would be willing to undergo the intervention again;<br>Drop-out: 0 |
| (Özkul et al.[23]); Turkey | Randomized control crossover trial;<br>I1: $n = 12$,<br>I2: $n = 12$;<br>Hospital | Spinal cord injury;<br>Total: 32.3 (13.0);<br>Wheelchair | • Neuropathic pain: 1) Pain severity (Visual Analog Scale): After intervention, daily post-treatment pain intensity decreased by 19.8–26.8%[a] in both groups, no significant changes in minimal, maximal, and average pain intensity in the intervention group. 2) Pain quality (Numerical Pain Scale): In the intervention group, sharpness (95% $CI = 0.13$ to 0.95, Cohen's $d = 0.16$), hotness (95% $CI = 0.01$ to 0.83, Cohen's $d = 0.18$), unpleasantness (95% $CI = 0.02$ to 1.23, Cohen's $d = 0.18$), and depth (95% $CI = 0.01$ to 0.83, Cohen's $d = 0.17$) improved[a]. 3) Pain interference (Brief Pain Inventory): After intervention, improvement in pain on "ability to get around"[a] (95% $CI = 0.04$ to 0.12, Cohen's $d = 0.18$) | NR | Recruitment: NR<br>Satisfaction: NR<br>Adherence: NR;<br>Drop-out: 7.69% |
| (Gustin et al.[17]) USA | One group pre-post study;<br>I: $n = 7$;<br>Home | Spinal cord injury;<br>I: 45.1 (15.4);<br>Wheelchair | • Neuropathic pain: 1) Pain intensity: Average pain reduced post-intervention in Visual Analog Scale (Cohen's $d = 0.50$) and Numerical Rating Scale[a] (Cohen's $d = 0.46$). 2) Pain-Related Disability (Pain Disability Index): No significant change. 3) Pain interference (Numerical Rating Scale) and severity (Numerical Pain Scale): Marginal decrease in pain interference and severity ($p = 0.053$, 0.052) | • Thalamic γ-aminobutyric-acid (Magnetic resonance spectroscopy): Decreased after intervention[a] ($ES = -0.72$), but this change was not significant related to pain intensity | Recruitment: NR;<br>Satisfaction: NR;<br>Adherence: NR;<br>Drop-out: 0 |
| (Jordan et al.[21]); USA | One group pre-post study;<br>Study 1: $n = 35$;<br>Lit room | Spinal cord injury;<br>I: 47.5 (9.4);<br>Wheelchair | • Neuropathic Pain (10 Numeric Rating Scale): 1) Decrease in at-level pain in VW condition compared with virtual wheeling condition[a]. 2) No significant interaction was found between treatment and pain location | NR | Recruitment: NR;<br>Satisfaction: NR;<br>Adherence: All;<br>Drop-out: 0 |
| (Landmann et al.[22]); Switzerland | Feasibility study;<br>I: $n = 4$;<br>Paraplegia center | Spinal cord injury;<br>Total: 41.5 (15.7);<br>Wheelchair | • Neuropathic Pain: 1) Pain severity (Visual Analog Scale): 1 had a 31 mm reduction, while 3 experienced mild increases (1−7 mm). 2) Grade of chronification of pain (Mainz Pain Staging System): Decreased (2/3−0). 3) Pain intensity (Graded Chronic Pain Scale): 2 not change, 1 increased to grade 3 and 1 decreased to grade 3;<br>•Psychosocial (Depression, Anxiety, and Stress Scale): 1) Anxiety: Reduction ($n = 1$). 2) Depression: Clinical reduction ($n = 1$). 3) Stress: Reduction ($n = 1$);<br>•Catastrophic thinking (Pain Catastrophizing Scale): Decreased ($n = 3$);<br>•General well-being (Spinal Cord Injury Quality of Life Basic Data Set): No significant change | NR | Recruitment: NR;<br>Satisfaction: Moderate satisfaction (64–93.5)/100 score;<br>Adherence: All;<br>Drop-out: 0 |
| (López-Carballo et al. 2018); Spain[14] | One group pre-post study;<br>I: $n = 23$;<br>Hospital | Lower limb neuropathic pain;<br>I: 48.17 (14.1);<br>Walk | • Neuropathic Pain (Visual Analog Scale): 69.5% of participants improved in average global pain post-treatment[a] (Cohen's $d = 0.27$) | NR | Recruitment: NR;<br>Satisfaction: NR;<br>Adherence: NR;<br>Drop-out: NR |
| | Controlled experimental study;<br>I1: $n = 14$,<br>I2: $n = 14$; | Lower limb neuropathic pain;<br>I1: 53.14 (14.3),<br>I2: 52.57 (16.3) | • Neuropathic Pain (Brief Pain Inventory): Improvement in both computer and mirror + projector group post-treatment[a] (Cohen's $d = 0.64$, 0.47, respectively) | NR | |

**Table 1 (continued) | Overview of Study Design, Population, Health Outcomes, and Feasibility of Virtual Walking Interventions**

| Study characteristics | | | Outcomes and findings | | |
|---|---|---|---|---|---|
| **Author, Year; Country** | **Study design; Sample size; Setting** | **Population (Disease, Age (Mean (SD) years), Mobility)** | **Health-related outcomes** | **Neurological mechanism** | **Feasibility and acceptability** |
| (Richardson et al.[24]); USA | Randomized control trial;<br>I: $n = 30$,<br>C: $n = 29$;<br>Lit room | Spinal cord injury;<br>I: 47.3 (12.0),<br>C: 43.0 (11.8);<br>Walk | • Neuropathic Pain: 1) Numerical Rating Scale: Decreased in VW group[a], no significant difference between-group. 2) Numerical Pain Scale: Pain symptoms reduced in cold, deep and skin sensitivity in VW compared to control[a] (Cohen's $d = 0.97, 0.98, 0.98$, respectively)<br>•Pain unpleasantness (Numerical Pain Scale): Reduction in VW compared to virtual wheeling group[a] (Cohen's $d = 0.99$) | NR | Recruitment:98.3%;<br>Adherence: 100%;<br>Satisfaction: NR;<br>Drop-out: 0 |
| (Roosink et al.[25]); Canada | One group pre-post study;<br>I: $n = 9$;<br>NR | Spinal cord injury;<br>I: 53.0 (13.9);<br>Wheelchair: 6, walk: 3 | • Pain intensity: No significant change | NR | Recruitment: NR;<br>Adherence: NR;<br>Satisfaction: Positive interaction with the avatar;<br>Drop-out: NR |
| (Soler et al.[2]); Spain | Controlled experimental study;<br>I: $n = 65$,<br>C: $n = 65$;<br>Hospital | Spinal cord injury;<br>I: 49.0 (14.9),<br>C: 48.0 (14.6);<br>Wheelchair | • Neuropathic Pain (Neuropathic Pain Symptom Inventory): 1) Improvement in VW group compared to control group post-treatment[a] (Cohen's $d = 0.20$). 2) Improvements in pain types: burning (Cohen's $d = 0.20$), squeezing (Cohen's $d = 0.14$), electric shocks (Cohen's $d = 0.22$), stabbing (Cohen's $d = 0.20$), pain from touch (Cohen's $d = 0.18$), pins and needles (Cohen's $d = 0.08$), and tingling (Cohen's $d = 0.22$) in tDCS+VW group[a]<br>•Depression (Patient Health Questionnaire-9): Improved in tDSC+VW group post-treatment[a] (Cohen's $d = 0.30$) | NR | Recruitment: 83.33%;<br>Adherence: 97.69%;<br>Satisfaction: NR;<br>Drop-out: 2.31% |
| (Trost et al.[19]); Australia | Controlled experimental study;<br>I: $n = 17$,<br>C: $n = 10$;<br>Home | Spinal cord injury;<br>Total: 42.5 (12.4);<br>Wheelchair | • Neuropathic Pain: Reduction in pain intensity (Numerical Rating Scale), neuropathic pain (Numerical Pain Scale) and pain-related activity interference (Numerical Rating Scale) in interaction group post-intervention[a] (Cohen's $d = 0.31, 0.34, 0.18$, respectively)<br>•Mood and affect (Positive and Negative Affect Schedule): Improved in interactive groups post-treatment[a] (Cohen's $d = -0.16$);<br>•Depression (Patient Health Questionnaire-9): Decreased in both groups[a] (Cohen's $d = 0.13, 0.10$, respectively) | NR | Recruitment: NR;<br>Adherence and Satisfaction: Not report difficulty completing the virtual reality protocol;<br>Drop-out: NR |
| (Villiger et al.[26]); Switzerland | One group pre-post study;<br>I: n = 12;<br>Home | Incomplete spinal cord injury;<br>I: 60.0 (10.2);<br>Wheelchair | • Physical Function: 1) Lower limb muscle strength (Lower Extremity Motor Score): Improved post-intervention[a]. 2) Balance (Berg Balance Scale): Improved post-intervention[a]. 3) Functional mobility (Timed Up and Go): Improved post-intervention, maintained at follow-up[a]. 4) No significant effects on walking speed/distance (10 m walking test) and mobility (Walking Index for Spinal Cord Injury II) post-treatment | NR | Recruitment: NR;<br>Satisfaction: NR;<br>Acceptance: Training was well accepted by the patients;<br>Drop-out: NR |
| (Yilmaz et al.[27]); Turkey | Randomized control trial;<br>I: $n = 23$,<br>C: $n = 23$;<br>Physiotherapy Clinic | Non-specific lower back pain;<br>I: 42.3 (10.9),<br>C: 52.8 (11.5);<br>Walk | • Pain (Visual Analog Scale): Decreased in VW group compared to control group post-treatment[a] (Cohen's $d = 0.28$);<br>•Physical Function: 1) Functional mobility (Timed-up and go Test, 6-Minute Walk Test): Improved in VW group compared to control group post-treatment[a] (Cohen's $d = 0.77, 0.72$, respectively). 2) Balance (Single leg balance test): No significant difference between-group;<br>• Fear of movement (TAMPA Kinesiophobia Scale): Decreased in VW compared to control group post-treatment[a] (Cohen's $d = 0.82$);<br>• Health-related quality of life (Nottingham Health Profile): No significant difference between-group | NR | Recruitment: 85.19%;<br>Acceptance: NR;<br>Satisfaction: NR;<br>Drop-out: 4.35% |

*C* Control, *fMRI* Functional magnetic resonance imaging, *I* Intervention, *NR* Not reported, *tDCS* Transcranial Direct Current Stimulation, *VW* Virtual walking.
[a]The intervention/trial is statistically significance.

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**Table 2 | Content, Modality, Interface, Locomotion Method, Instructors, and Side Effects of Virtual Walking Interventions**

| Author; Year | Treatment content | Control types | Virtual modality; Dosage (Duration, Frequency, Total time) | Interface | Virtual locomotion method | Virtual walking only or not | Instructor | Side effect |
|---|---|---|---|---|---|---|---|---|
| Eick et al.[20] | Observation of an actor walking from a 1st-person view; imagined walking without actual limb movement | Active control: Able-body participants experience the treatment content | Virtual illusion; 8 min in total, repeated 4 times of stimuli | Projection screen | Passive observing moving | Yes | NR | NR |
| Mollà-Casanova et al.[1] | Simultaneous observation of the illusion of walking legs overlay of patient's own upper body supported by a standing frame | Active control: Viewing videos of landscape without any type of human movement projected | Virtual illusion; 10 min per session, 3 times a week, 6 weeks, 18 sessions | Projection screen + mirror | Passive observing moving | No, combined with therapeutic exercise | Physical therapists: Therapeutic exercise | Fatigue; dizziness while viewing placebo VW video on the second session ($n = 1$) |
| Özkul et al.[23] | Simultaneous observation of an avatar walking with the patient's own body; followed by a 1-week washout period and subsequent application of transcutaneous electrical nerve stimulation | Active control: Transcutaneous electrical nerve stimulation for 2 weeks, 1 week washout, then VW | Virtual avatar; 15 min per session, 5 times per week, 2 weeks, 10 sessions | Projection screen + mirror | Passive observing moving | No, combined with Transcutaneous Electrical Nerve Stimulation | NR | NR |
| Gustin et al.[17] | Observation and controlling the walking avatar, translating arm movements to leg movements using handheld controller in a virtual environment from 1st-perspective, with incentivization for progress | / | Virtual avatar (1st-person view); 20 min per session, 10 days within 2 weeks | Head-Mounted Display (HTC Vive) | Arm swing locomotion | Yes | Research assistant: Set up equipment in peoples' homes | None |
| Jordan et al.[21] | Simultaneous viewing of 1st-person views walking video and imagining themselves performing the movement | | Virtual illusion; 20 min in total | 3D monitor | Passive observing moving | Yes | NR | NR |
| Landmann et al.[22] | Observation of computer-generated overlay of animated legs on their upper body, walking in forest from a 3rd-person view | / | Virtual illusion; twice a week for five weeks (or 5 times per week for 2 weeks), 10 sessions | Projection screen + build-in camera | Passive observing moving | Yes | Therapist: Supervision & support | Long sleep period after the third treatment, and a feeling like a blackout or memory lapse after waking up ($n = 1$) |
| López-Carballo et al. 2018[14] | Test trial: Observation of algorithm-generated overlay of a recorded walking legs on their upper body to create walking illusion with arm swing used to control gait cycle in a virtual environment, incentivized by matching target speed plus | | Virtual illusion; 20 min per session, 10 sessions | Computer Screen | Arm swing locomotion | No, combined with Transcranial Direct Current Stimulation | NR | NR |
| | Clinical trial: Group 1: Simultaneous observation of the illusion of walking legs and the patient's own upper body Group 2: Same as the test trial | / | Virtual illusion; 20 min per session, 10 sessions | Group 1: Projection screen + mirror, Group 2: Same as the test trial | Group 1: Passive observing moving Group 2: Same as the test trial | No, combined with Transcranial Direct Current Stimulation | NR | NR |
| Richardson et al.[24] | Simultaneous viewing of 1st-person views walking video and imagining themselves performing the movement | Active control: Same actor propelling a manual wheelchair along the same path | Virtual illusion; 20 min per session, 1 session in total | 3D monitor | Passive observing moving | Yes | Examiner: Played video | NR |

**Table 2 (continued) | Content, Modality, Interface, Locomotion Method, Instructors, and Side Effects of Virtual Walking Interventions**

| Author; Year | Treatment content | Control types | Virtual modality; Dosage (Duration, Frequency, Total time) | Interface | Virtual locomotion method | Virtual walking only or not | Instructor | Side effect |
|---|---|---|---|---|---|---|---|---|
| Roosink et al.[25] | Experience interactive and static virtual walking, combined with imagining themselves walking while swinging their arms | / | Virtual avatar & illusion; 90 min per session, 2 weeks, 2 sessions | 3D glasses+ Silver-coated projection screen | Passive observing moving | Yes | NR | Increased transient musculoskeletal pain ($n = 1$), physical fatigue ($n = 4$), and difficulties to maintain attention ($n = 2$) |
| Soler et al.[2] | The system combines patient's upper body own and an animated digital image representing the movement of walking legs or movement of arms | Inactive control: Monitoring the stability of pain measurement | Virtual illusion; 20 min per session, for 2 weeks, 10 sessions | Projection screen + Red-Green-Blue Depth camera | Passive observing moving | No, combined with Transcranial Direct Current Stimulation | NR | Mild headache (mainly in the first session) ($n = 6$), some feeling tired, a transient increase in neurological pain ($n = 2$) at the end of treatment |
| Trost et al.[16] | Observation of walking avatar from 1st-person view, controlling movement by translating arm movements to leg movements using wireless handheld controller in a virtual environment, with incentivization through walking | Active control: Observing a pre-record video-like progression in 1st-person view of virtual walking | Virtual avatar; 30 min per session 2 gameplay, 10 days, 20 sessions | Head-Mounted Display (HTC Vive) | Arm swing locomotion | Yes | Research assistant: Set up equipment in peoples' homes | NR |
| Villiger et al.[26] | Simultaneous legs movement execution and observation in 1st person view in four virtual games. One scenario "Activity of Daily living", subjects alternately lift their feet to make the virtual avatar walking | / | Virtual avatar; 30–45 min per session, 4 weeks, 16–20 sessions | Computer screen | Foot Tracking Locomotion | Yes | Therapist: Supervision and collect data | NR |
| Yilmaz et al.[27] | Simultaneous viewing of 1st-person views walking video filmed by a cameraman walking naturally through an Irish forest, participants imagined themselves walking | Active control: Traditional physical therapy | Virtual illusion; 15 min per session, 2 weeks, 10 sessions | Video glasses (Vuzix Wrap 920) | Passive observing moving | Yes | Physiotherapist: Supervision patient's exercises | NR |

*NR* Not reported, *VW* Virtual walking.

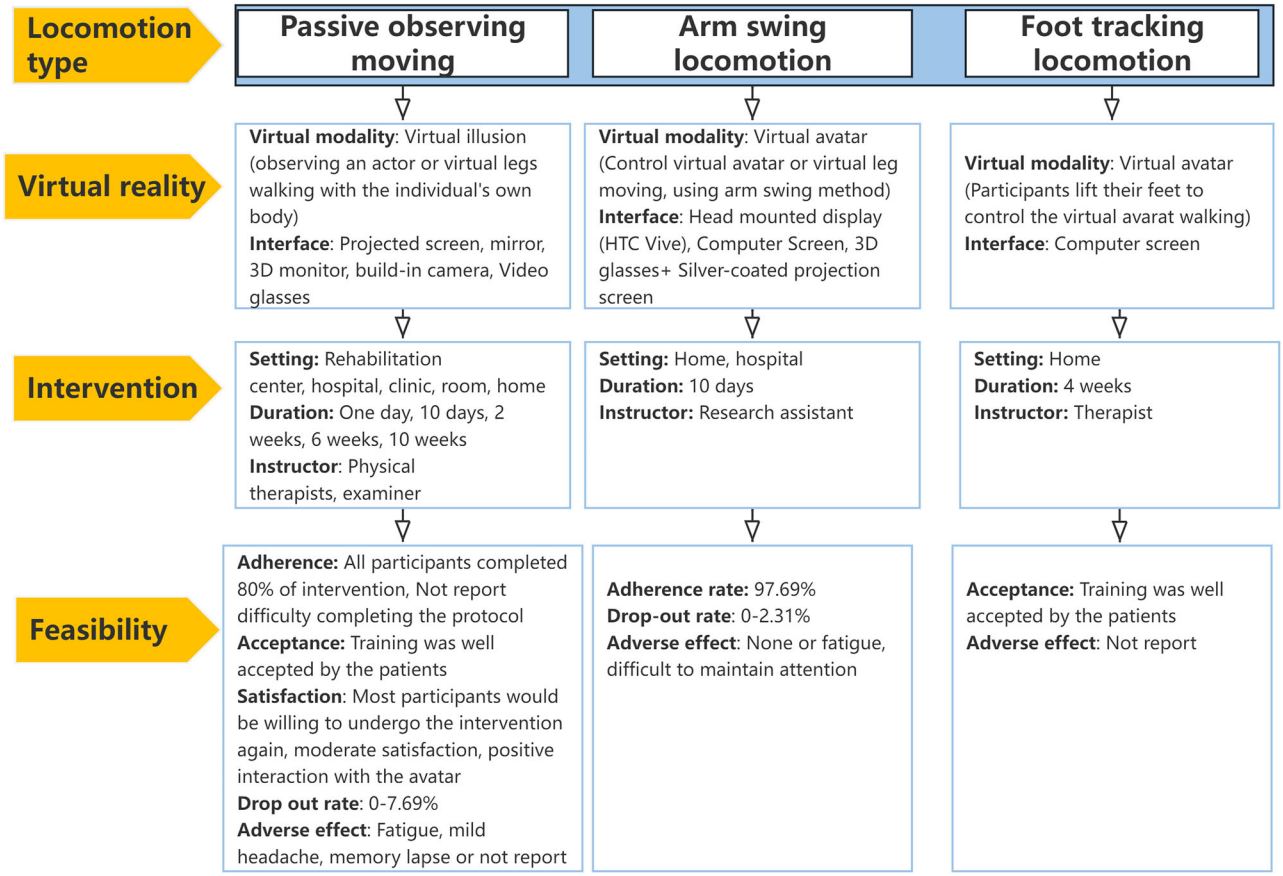


**Fig. 2 | Categorization of virtual walking locomotion types and feasibility.** The figure categorizes three types of virtual walking locomotion, detailing their associated virtual modality, intervention characteristics, and feasibility for practice.

(7.2%)[26]. Regarding passive observing moving, the detailed tasks contain three observations: observing a pre-recorded actor walking from the first perspective[20,21,24], observing virtual leg movement combined with one's own upper body in a mirror from the first perspective[1,14,23], and observing a computer-generated overlay of virtual leg movement combined with one's own upper body from the first perspective[2,14,27] or the third perspective[22,25]. For arm swing, tasks comprise using a handheld controller or arm gesture to control virtual leg movement from the first perspective[16,17] or the third perspective[14], with the game containing incentive elements[16]. For foot tracking locomotion, the task is that people lift their feet to control the virtual avatar walking[26]. Figure 2 illustrates the categorization of virtual walking locomotion types.

The interface includes a projection screen (42.8%) (a projection screen only (7.1%)[20], a combination of mirror (21.4%) or camera (14.3%))[1,2,14,22,23]. The 3D monitor or 3D screen with glasses accounted for 21.4%[21,24,25], followed by HMDs (14.3%)[16,17] and computer screens (14.3%)[14,26]. Only one study used video glasses (7.1%)[27].

Regarding the duration of one virtual walking session, 53.8% of the studies set the duration at 11–20 min[2,14,17,21,23,24,27], and 15.4% of studies set it at 8–10 min[1,20]. Concerning the frequency of virtual walking, more than half of the studies (70.0%) reported a frequency of 4–5 times per week or daily[2,16,17,22,23,26,27], while 30.0% of interventions were implemented at a frequency of 1–3 times per week[1,14,25]. Additionally, three studies were one-time interventions and were not included in the frequency calculations[20,21,24]. The instructors were either therapists or research assistants[1,16,17,22,24,26,27]. In one study, the therapist implemented additional physical therapy[1]. Research assistants primarily assisted in setting up VR equipment or playing video ($n = 3$)[16,17,24], while supervising the whole process ($n = 3$)[22,26,27] and collecting data related to the supervision ($n = 1$)[26] were mainly conducted by the therapists. For details, see Table 3.

## Results of virtual walking on health-related outcomes

Both passive observing and arm swing interventions were evaluated for their effects on pain-related outcomes[1,2,14,16,17,21–25,27]. For passive observing interventions, most studies reported significant improvements in pain intensity or severity post-intervention[14,21–24,27], with two studies showing significant between-group differences compared to active controls[21,27]. However, two studies found no significant differences between groups[1,25]. Regarding other pain-related outcomes, such as pain symptoms, pain-related activity interference, and pain qualities, most studies reported significant decreases in the intervention group[2,23,24], including two with active controls[23,24] and one single-group study[2]. For arm swing interventions, included studies demonstrated significant improvements in pain intensity or severity post-intervention[14,16,17]. Regarding other pain-related outcomes, one study found a significant decrease in pain interference in the intervention group[16], while another reported no significant changes in pain-related disability post-intervention[17].

Both passive observing and arm swing interventions were evaluated for psychosocial outcomes[2,16,22,24,27]. For passive observing interventions, studies reported significant improvements in depression within groups post-intervention[2,22]. Significant between-group improvements were also observed for fear of movement and pain unpleasantness, with both studies using active controls[24,27]. Additional positive effects on mood, anxiety, stress, and catastrophic thinking were noted post-treatment[22]. However, no significant between-group differences were observed for general well-being or quality of life[22,27]. For arm swing interventions, only one study examined psychosocial outcomes, reporting improvements in depression, mood, and affect post-intervention. An active control was adopted[16].

Physical function outcomes were assessed in passive observing and foot tracking interventions[1,26,27]. Passive observing interventions showed significant improvements in lower limb muscle strength, walking speed,

**Table 3 | Numerical Summary of Virtual Walking Settings and Intervention Delivery**

| Category | Details[c] | N | ~% |
|---|---|---|---|
| Virtual walking setting | | | |
| *Virtual modality* | | | |
| | Virtual avatar[16,17,23,25,26] | 5 | 35.7 |
| | Virtual illusion[1,2,14,20–22,24,25,27] | 9 | 64.3 |
| *Locomotion method* | | | |
| | Passive observing moving[1,2,14,20–25,27] [a] | 10 | 71.4 |
| | Arm swing locomotion[14,16,17] [a] | 3 | 21.4 |
| | Foot Tracking Locomotion[26] | 1 | 07.2 |
| *Interface* | | | |
| | Projected screen only[20] | 1 | 07.1 |
| | Projected screen + mirror[23,14] [b] | 3 | 21.4 |
| | Projected screen + camera[2,22] | 2 | 14.3 |
| | Computer screen[14,26] [a] | 2 | 14.3 |
| | 3D monitor/ 3D screen with glasses[21,24,25] | 3 | 21.4 |
| | Head-Mounted Display[16,17] | 2 | 14.3 |
| | Video glasses[27] | 1 | 07.1 |
| *Combination* ($n = 4$) | | | |
| | Transcranial Direct Current Stimulation[2,14] | 2 | 50.0 |
| | Transcutaneous Electrical Nerve Stimulation[26] | 1 | 25.0 |
| | Therapeutic exercise[1] | 1 | 25.0 |
| Delivery dosages | | | |
| *Length of each session* (min) | | | |
| | 8–10[1,20] | 2 | 15.4 |
| | 11–15[23,27] | 2 | 15.4 |
| | 16–20[2,14,17,21,24] | 5 | 38.4 |
| | > 20[16,25,26] | 3 | 23.1 |
| | Not report[22] | 1 | 07.7 |
| *Frequency/week* ($n = 10$)[d] | | | |
| | 1–3[1,14,25] | 3 | 30.0 |
| | 4–5[2,22,23,26,27] | 5 | 50.0 |
| | Daily[16,17] | 2 | 20.0 |
| *Duration* (day) | | | |
| | 1[20,21,24] | 3 | 23.1 |
| | 10–14[2,16,17,23,25,27] | 6 | 46.1 |
| | 4–6 weeks[1,22,26] | 3 | 23.1 |
| | Not report[14] | 1 | 07.7 |

[a]Indicates the first trial.
[b]Indicates the second trial.
[c]Number in square brackets correspond to the full citations in the manuscript reference list.
[d]One-time experiment is excluded from frequency calculations.

walking distance, and functional mobility post-intervention[1,27], with one study reporting significant between-group differences in functional mobility[27]. However, no significant between-group differences were observed for balance[27]. Foot tracking interventions demonstrated significant improvements in functional mobility, balance, and lower limb muscle strength post-intervention compared to active controls[26]. Functional mobility effects were maintained during follow-up, although walking performance did not show significant changes[26]. For details, please see Table 4.

Only two studies explored the mechanisms underlying virtual walking on neurological-related outcomes[17,20], which can be classified into two categories: biochemical mechanism ($n = 1$) and neurological mechanism ($n = 1$). For biochemical mechanism, Gustin et al.[17] tested the effects of virtual walking for patients with SCI on thalamic γ-aminobutyric-acid (GABA) and neuropathic pain. The GABA increased statistically after virtual walking; however, this change was not significantly related to pain intensity and duration (though the Pearson correlation coefficient was at a moderate level, $r = -0.4$). For neurological mechanisms, Eick et al.[20] used functional magnetic resonance imaging (fMRI) to reveal that there was an activation in the bilateral somatosensory cortex and paracentral lobule for paraplegic patients during the virtual walking process.

### The feasibility, acceptability, and adverse effects of virtual walking

Four studies reported recruitment rates[1,2,24,27] ranging from 80.0% to 98.3% (the median rate is 84.2%). Participants' drop-out rates in the virtual walking group ranging from 0%[24] to 7.7%[23] (the median value is 0). Seven studies reported an intervention adherence rate of 97.7–100%[1,2,16,20–22,24]. Our studies reported satisfaction with the intervention[1,16,22,25]; one showed moderate satisfaction[22], another showed 91.7% of the participants would be willing to participate in the intervention again[1], and one reported no difficulty in completing the protocol[16]. One reported positive interaction with a virtual avatar[25]. Regarding adverse effects, severe adverse effects were not reported in the virtual walking intervention, but three studies reported fatigue[1,2,25], one reported dizziness[1], one reported feeling blackout after waking up[22], and two reported increased pain but disappeared at the end of the session[2,25].

### The methodological quality of studies

The quality assessment of the studies revealed a total of four RCTs[1,23,24,27] and nine quasi-experiment studies[2,14,16,17,20,21,24–26] out of 13 included studies. Of the RCTs, three studies did not provide details on the method of randomization and allocation (75.0%)[23,24,27]. For the quasi-experiment studies, six studies (66.7%) lacked a control group design[17,20–22,25,26], and four studies (44.4%) did not clearly describe the outcomes measurement[14,17,21,22]. Additionally, most studies did not perform multiple time-point and follow-up assessments (66.7%–77.8%)[2,14,17,20,21,25]. The detailed results are presented in Supplementary Tables 2, 3.

## Discussions

This scoping review highlights that virtual walking can serve as a promising non-pharmacological therapy for improving pain, physical mobility, and psychosocial outcomes such as depression. The intervention is generally well-accepted and satisfying, particularly among individuals with disabilities. However, significant heterogeneity in study designs, locomotion methods, and outcome measures limits direct comparisons and the ability to draw firm conclusions. Future research should focus on clarifying these mechanisms, standardizing protocols, and evaluating long-term effects to optimize its therapeutic potential.

The majority of the populations included were individuals with SCI[1,17,20,22–24], while other studies focused on conditions such as lower back pain or limb pain[14,27]. Previous reviews have highlighted the benefits of virtual exercise for patients with mobility limitations, including those with stroke, SCI, or multiple sclerosis[28]. In particular, patients with SCI often experience neuropathic pain; VR has shown promise as a distraction that can alleviate pain[18]. Additionally, studies involving patients with mild to moderate depression showed improved depressive symptoms[2,16,22], possibly due to the activation of volitional and reward processing circuits. A study pointed out that VR behavior activation for adults with major depressive disorder has been used in a feasibility RCT, showing it is safe and without adverse events[29]. Future research can explore the efficacy of virtual walking across a broader range of mobility impairments and different levels of depression.

Three types of locomotion methods were classified, with passive observing being prominent[1,2,14,20–25,27]. The intervention was first proposed in 2007, called mirror therapy, which provides visual illusions for patients with SCI and lets them experience the feeling of walking. These effects of pain relief lasted till three months of follow-up[12]. With the development of VR technology, recent studies have adopted more simulated and interactive

**Table 4 | Graphic representation of the effects of virtual walking on health-related outcomes by included studies**

| Locomotion categories, Study, Year | Changes in Pain (11) | | | | | Changes in psychosocial outcomes (5) | | | | | | | | Changes in physical function (3) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Severity/ intensity | Quality | Interference | Pain-related disability | Pain symptoms | Depression | Anxiety | Stress | Catastrophic thinking | General well-being | Pain unpleasantness | Mood and affect | Fear of movement | Muscle Strength | Walking speed/ distance | Balance | Function mobility |
| **Passive observing locomotion** | | | | | | | | | | | | | | | | | |
| Eick et al.[20] | | | | | | | | | | | | | | | | | |
| Mollà-Casanova et al.[1] ▲ | - | | - | | | | | | | | | | | ■* | ■* | | |
| Özkul et al.[23] ▲ | ○* | ○* | ○* | | | | | | | | | | | | | | |
| Jordan et al.[21] | ○* | | | | | | | | | | | | | | | | |
| Landmann et al.[22] | ■ | | | | | ■ | ■ | ■ | ■ | - | | | | | | | |
| López-Carballo et al.[14] ▲ | ■* | | | | | | | | | | | | | | | | |
| Richardson et al.[24] | ■* | | | | ○* | | | | | | ○* | | | | | | |
| Roosink et al.[25] | - | | | | | | | | | | | | | | | | |
| Soler et al.[2] ▲ | | | | | ■* | ■* | | | | | | | | | | | |
| Yilmaz et al.[27] | ○* | | | | | | | | | - | | | ○* | | | - | ○* |
| Arm swing locomotion | | | | | | | | | | | | | | | | | |
| Gustin et al.[17] | ■* | | - | - | | | | | | | | | | | | | |
| López-Carballo et al. [14] ▲ | ■* | | | | | | | | | | | | | | | | |
| Trost et al.[16] | ■* | | ■* | | | ○* | | | | | | ■* | | | | | |
| Foot tracking locomotion | | | | | | | | | | | | | | | | | |
| Villiger et al.[26] | | | | | | | | | | | | | | ■* | - | ■* | ■* |

note. - = Outcomes reported as non-significant, ▲ = Virtual walking combined with other therapies; ■ = Improved within the intervention group, but without statistical significance explicitly stated (e.g., feasibility studies), ○ = Improved between-group.
*$P$ <0.05.

locomotion methods, such as arm swing and foot tracking, to provide a more immersive and realistic virtual walking experience[16,17]. The heterogeneity of locomotion methods highlights the need to tailor interventions to individual patient needs. For patients with limited upper extremity function and mobility impairments, passive observing moving may be appropriate due to its minimal physical interaction[23,30]. And those with intact upper extremity function can benefit from arm swing locomotion for a more interactive experience[16]. For those with mild mobility limitations, foot tracking locomotion offers a relatively realistic walking experience[26]. The integration of AI to analyze users' behavior and preferences can optimize the interactions between patients and the virtual environment, enhancing patient adherence and interest[31].

Regarding settings, most studies were conducted in clinical environments, likely due to equipment and space constraints. In-home settings, virtual walking interventions are increasingly feasible, with studies showing the use of both screens and HMDs. People can choose interfaces according to their own needs and functional ability. For example, passive observing tasks can use projection or computer screens, arm swing locomotion often requires HMDs for greater immersion, and foot tracking requires screens with cameras to capture movement. HMDs are promising for home use, as they offer a more immersive experience compared to 2D or 3D screens[32–34]. In this context, using gesture-based interventions on affordable mobile VR platforms, such as Google Cardboard, presents a viable alternative[35].

The dosage in virtual walking is critical, as it influences the effects. Studies with longer sessions did not always show significant pain reduction. Roosink et al.[25] conducted two 90 min sessions, but the pain intensity did not significantly change. In another study set of 20 sessions, decreased pain intensity was observed; however, the long-term benefit remains unclear[16], suggesting the need to establish a dose-response relationship. This study also pointed out that the safe maximum of participants' exposure to immersive gameplay was 20 min for 2 sessions and at least 4 h apart within 2 weeks, which provides a reference for future research[16].

Virtual walking interventions may have potential benefits for various health-related outcomes, including pain relief, psychosocial well-being, and physical function. Most passive observing interventions and arm swing interventions demonstrated moderate effect sizes in improving pain intensity for individuals with SCI and lower back or limb pain[14,17,22,23]. Although the protocols differed between individuals with SCI and those without neurological impairments, both emphasized the use of visual illusions and walking simulations[16,22], this component of virtual walking can restore congruence between sensory and visual input, potentially reversing maladaptive neural changes and reducing pain in the short term[36]. Improvements were also observed in various dimensions of pain, such as pain quality, pain function, and pain symptoms, potentially due to differences in virtual settings and intervention content[1,24,25]. For example, neuropathic pain phenotypes such as cold sensitivity, deep pain, and skin sensitivity showed significant reductions in the arm swing intervention, likely due to the recalibration of specific areas affected by neuropathic pain through visual input[24]. Future studies should identify specific pain phenotypes that benefit most from virtual walking and explore the underlying neurological pathways involved.

Combination therapies, such as tDCS and TENS, showed promising effects when integrated with virtual walking[1]. tDCS may enhance virtual walking's effects by activating descending pain modulation pathways, such as the anterior cingulate cortex and other areas related to pain perception[2]. TENS, on the other hand, appears to target pain intensity more directly, leading to greater reductions in pain-related impacts on relationships and sleep[23]. These findings suggest that virtual walking could serve as a non-pharmacological adjunct for pain management. Future studies should explore its long-term effects and synergistic potential with other non-pharmacological therapies.

Virtual walking also showed potential benefits for psychosocial outcomes, including improvements in depression, anxiety, stress, mood, and affect[2,16,22,27]. Both passive observing and arm swing interventions showed small effect sizes for these outcomes, likely due to the emotional distraction and engagement provided by the virtual environment[37,38]. Fear of movement and pain unpleasantness, which are closely linked to anxiety and depressive symptoms, showed large effect sizes in both passive observing and foot tracking interventions, possibly due to virtual walking's effectiveness in acute pain relief[39]. However, changes in quality of life were not significant, potentially due to the short intervention duration[22,27]. Given the limited number of studies and the inclusion of only one RCT on mood-related outcomes, future RCTs are needed to further investigate the effectiveness of virtual walking on psychosocial well-being.

The large effect size for physical function was observed in a foot-tracking locomotion RCT for individuals with lower back pain, followed by those with SCI. Foot tracking interventions use movement observation and repetitive motivational scenarios to stimulate the action processing system, promoting muscle strength and mobility recovery[1,26,27]. For individuals with SCI, virtual walking offers a convenient and engaging method of exercise, with evidence suggesting its ability to modulate cortical sensorimotor integration[40]. More rigorous studies are warranted to determine whether the benefits of virtual walking interventions can be generalized to other populations with neurological disorders.

Two studies in this review investigated the neurological mechanisms underlying the effects of virtual walking on pain[17,20]. Regarding the biochemical level, although previous research linked neuropathic pain to reduced thalamic GABA levels[41], recent evidence suggests that GABAergic neurons in the central amygdala could help regulate immune responses involved in pain[39]. At the neurological level, the included study found that virtual walking activated the bilateral somatosensory cortex in patients with neuropathic pain compared to healthy controls, suggesting that this activation may play a role in pain modulation[20]. The somatosensory cortex activation may provide afferent inputs that counteract the loss of sensory signals, potentially reversing maladaptive cortical reorganization—a process linked to ongoing pain relief in individuals with spinal cord injury[42]. Together, these findings indicate that virtual walking may modulate multiple neural pathways, especially those associated with sensory processing and motor imagery, which could contribute to its analgesic effects[42]. Future studies should explore how these mechanisms including possible changes in GABAergic activity, contribute to pain reduction.

A few studies reported on the clinical feasibility ($n = 5$)[1,2,22,24,27], with participants expressing great satisfaction and acceptance. Satisfaction levels appeared to be influenced by the locomotion methods and the degree of immersion. For instance, some participants reported difficulty in fully immersing themselves when viewing avatars from a third-person perspective[22]. Using HMDs and ensuring greater visual congruence between virtual leg and real arm movements were identified as strategies to improve satisfaction[25]. Although feedback was largely positive, minor adverse effects such as fatigue, mild headaches, and dizziness were reported, though these effects were transient[1,2,22,25]. Fatigue may stem from prolonged screen use, as a VR risks review pointed out that using HMDs for over 26.22 min can induce visual fatigue[43]. Dizziness, likely caused by mismatched visual and physical inputs, may lead to motion sickness[44]. Incorporating simultaneous haptic feedback on feet or lower limbs, along with techniques like peripheral blurring and field of view reduction, could help mitigate these effects[45,46].

This review has several limitations. First, the small number of included studies limits the ability to generalize findings. Second, there was methodological variability among the studies, as they featured three different locomotion methods, and two-thirds were non-randomized controlled trials. As a result, the effects of virtual walking interventions should be interpreted with caution. Third, only English-language articles were included, which introduces potential publication and language bias. This means the findings may not fully represent research conducted in non-English-speaking settings or published in non-English journals. These limitations highlight the need for more large-scale, high-quality randomized controlled trials to strengthen the evidence base for virtual walking interventions.

In conclusion, this scoping review suggests that virtual walking may have potential benefits for individuals with SCI or lower back pain,

including improvements in pain, function, mobility, and depression. The intervention is associated with only mild side effects, which tend to diminish over time. Virtual walking encompasses three locomotion methods and is typically delivered through screens; however, portable HMDs are also feasible for implementation in home settings. Preliminary findings also suggest that the somatosensory cortex is activated during virtual walking, but the specific mechanisms for virtual walking and psychosocial-related outcomes need further identification. Given the promising effects of virtual walking on health-related outcomes, future studies with more rigorous designs (e.g., RCTs), larger sample sizes, and inclusion of patients from different mobility levels are recommended to enhance the validity and representativeness of findings. Additionally, studies should explore the feasibility of implementing virtual walking interventions in accessible settings, such as home-based environments, and consider tailoring the choice of interfaces (e.g., HMD for immersive experiences or projection screens for users with upper limb impairments) to meet the specific needs and preferences of different populations. Finally, future research is encouraged to explore the specific neurological mechanisms underlying the effects of virtual walking on health-related outcomes, particularly its impact on pain and psychosocial outcomes. It could provide insights to maximize the therapeutic effectiveness.

## Methods

This scoping review followed the methodological guidance outlined in the Joanna Briggs Institute's (JBI) Manual for Evidence Synthesis and is reported in accordance with the PRISMA Extension for Scoping Reviews (PRISMA-ScR) checklist[47]. The scoping review was registered in the Open Science Frame (OSF) at https://osf.io/rv6g5/.

### Selection of studies

The inclusion and exclusion criteria were developed following the Population, Concept, and Context (PCC) framework. The population consisted of adults aged 18 years or older, with no restrictions on specific diseases or demographic characteristics (e.g., ethnicity or socioeconomic status). The concept focused on virtual walking interventions or interventions incorporating virtual walking components and reporting health-related outcomes. The context included a variety of interventional study designs, such as RCT, quasi-experimental studies, and other experimental studies. Studies were excluded if they were abstract-only, conference proceedings, protocols, or lacked full-text availability. Only studies published in English were included. This broad inclusion aimed to comprehensively map the landscape of research on virtual walking interventions, as detailed in the introduction.

The search strategies were developed by using combinations of keywords surrounding "virtual reality", "walking", and "clinical trials". These strategies were collaboratively formulated and refined by two reviewers (D.Y.S. and L.J.Y.). The detailed search strategies, including search strings and database-specific adjustments, are provided in Supplementary Table 1. Two independent reviewers (D.Y.S. and L.J.Y.) screened all records, with a third reviewer (L.Y.) mediating any discrepancies through consensus.

Twelve databases (PubMed, Web of Science, ClinicalTrials, Science Direct, Embase, Cumulative Index to Nursing and Allied Health Literature (CINAHL), Cochrane Library, Psycho Info, IEEE Xplore and Education Resources Information Center (ERIC), ProQuest Dissertations & Theses (PQDT) and Bielefeld Academic Search Engine (BASE)) were systematically searched from 01/01/2014 to 08/10/2024. Reference lists of included studies were also screened. Although the concept of virtual walking was first introduced in 2007, and a review conducted in 2014 that included virtual walking studies as part of its analysis[12,13], significant advancements have been made in virtual walking interventions. To highlight the latest developments, this scoping review focuses on literature from 2014 to 2024.

### Data extraction

Two independent reviewers (D.Y.S. and L.J.Y.) developed an extraction template and independently extracted data from the included studies. The following data were collected: author, publication year, country, study design, sample size, setting, population, intervention-related content (including treatment details, virtual modality, interface, locomotion method, and whether the intervention involved virtual walking exclusively), intervention dosage, instructors, control types, and health-related outcomes. For health-related outcomes, the extracted data were categorized into three key fields: pain, psychosocial outcomes, and physical function. The categories reflect the most commonly reported outcomes in the included studies and align with the World Health Organization's International Classification of Functioning, Disability, and Health (ICF) framework for rehabilitation and disability research[48].

Assessment tools, results, neurological mechanisms, feasibility and acceptability, and side effects were also extracted. Feasibility indicators comprised the recruitment rate (the percentage of participants who gave consent divided by the number of eligible participants) and the drop-out rate (the percentage of participants who dropped out of the intervention after randomization divided by the total number of participants who agreed to consent). Acceptability indicators included participants' satisfaction with the interventions and the adherence rate (the percentage of participants who completed the intervention protocol as the researchers defined). Discrepancies were reconciled by consulting a third investigator (L.Y.)

### Quality of assessment

Two reviewers (D.Y.S. and L.J.Y.) independently evaluated the methodological quality of the included studies, with discrepancies reconciled by consulting a third investigator (L.Y.). RCT was assessed by the JBI critical appraisal tool for RCTs, which consists of 13 items rated as "yes", "no", "unclear", or "not applicable"[49]. Quasi-experiment study (QES) was assessed using the JBI critical appraisal tool for QES, which contained nine items with the same rating system[49].

### Synthesis of results

A narrative summary of the included studies was synthesized to map the literature according to the research questions. The data were presented using descriptive tables and diagrams and then summarized based on inductively developed objectives.

## Data availability

All data analyzed in this study are included in this article and its supplementary information files.

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## References

1. Mollà-Casanova, S. et al. Effectiveness of virtual-walking intervention combined with exercise on improving pain and function in incomplete spinal cord injury: a feasibility study. *Spinal Cord. Ser. Cases* **10**, 64 (2024).
2. Soler, D. et al. Transcranial direct current stimulation and visual illusion effect according to sensory phenotypes in patients with spinal cord injury and neuropathic pain. *J. Pain.* **22**, 86–96 (2021).
3. Austin, P. D. et al. The short-term effects of head-mounted virtual-reality on neuropathic pain intensity in people with spinal cord injury pain: a randomised cross-over pilot study. *Spinal Cord.* **59**, 738–746 (2021).
4. Hu, Y. et al. Effectiveness of telehealth interventions on cognitive function and quality of life in adults with neurologicaldisorders: a systematic review and meta-analysis. *J. Am. Med. Dir. Assoc.* **26**, 105491 (2025).
5. Pelletier, C. Exercise prescription for persons with spinal cord injury: a review of physiological considerations and evidence-based guidelines. *Appl. Physiol. Nutr. Metab.* **48**, 882–895 (2023).
6. Mat Rosly, M. et al. Exergaming for individuals with neurological disability: a systematic review. *Disabil. Rehabil.* **39**, 727–735 (2017).
7. Morgan, K. A. et al. Mobility disability and exercise: health outcomes of an accessible community-based center. *Front. Rehabil. Sci.* **3**, 836655 (2022).

8. Marsh, W. E. et al. Cognitive demands of semi-natural virtual locomotion. *Presence. Teleoperators Virtual Environ.* **22**, 216–234 (2013).
9. Janeh, O. & Steinicke, F. A Review of the potential of virtual walking techniques for gait rehabilitation. *Front Hum. Neurosci.* **15**, 717291 (2021).
10. Cohen, S. P. et al. Pain in the context of sensory deafferentation. *Anesthesiology* **140**, 824–848 (2024).
11. Sarupuri, B. et al. Triggerwalking: a biomechanically-inspired locomotion user interface for efficient realistic virtual walking. *Proceedings of the 5th Symposium on Spatial User Interaction*, (2017).
12. Moseley, L. G. Using visual illusion to reduce at-level neuropathic pain in paraplegia. *Pain* **130**, 294–298 (2007).
13. Roosink, M. & Mercier, C. Virtual feedback for motor and pain rehabilitation after spinal cord injury. *Spinal Cord.* **52**, 860–866 (2014).
14. Lopez-Carballo, J. et al. Gestural interaction and visual illusion for lower limbs' neuropathic pain treatment. *IEEE Trans. Neural Syst. Rehabil. Eng.* **26**, 2217–2225 (2018).
15. Saint-Aubert, J. et al. Influence of user posture and virtual exercise on impression of locomotion during VR observation. *IEEE Trans. Vis. Comput Graph* **29**, 3507–3518 (2023).
16. Trost, Z. et al. Immersive interactive virtual walking reduces neuropathic pain in spinal cord injury: findings from a preliminary investigation of feasibility and clinical efficacy. *Pain* **163**, 350–361 (2022).
17. Gustin, S. M. et al. Cortical mechanisms underlying immersive interactive virtual walking treatment for amelioration of neuropathic pain after spinal cord injury: findings from a preliminary investigation of thalamic inhibitory function. *J. Clin. Med* **12**, 5743 (2023).
18. Austin, P. D. & Siddall, P. J. Virtual reality for the treatment of neuropathic pain in people with spinal cord injuries: a scoping review. *J. Spinal Cord. Med.* **44**, 8–18 (2021).
19. Scalise, M. et al. Virtual reality as a therapeutic tool in spinal cord injury rehabilitation: a comprehensive evaluation and systematic review. *J. Clin. Med.* **13**, 5429 (2024).
20. Eick, J. & Richardson, E. J. Cortical activation during visual illusory walking in persons with spinal cord injury: a pilot study. *Arch. Phys. Med. Rehabil.* **96**, 750–753 (2015).
21. Jordan, M. & Richardson, E. J. Effects of virtual walking treatment on spinal cord injury-related neuropathic pain. *Am. J. Phys. Med. Rehabil.* **95**, 390–396 (2016).
22. Landmann, G. et al. Virtual walking therapy in neuropathic spinal cord injury pain: a feasibility study. *Spinal Cord. Ser. Cases* **10**, 53 (2024).
23. Özkul, Ç et al. Effects of visual illusion and transcutaneous electrical nerve stimulation on neuropathic pain in patients with spinal cord injury: a randomised controlled cross-over trial. *J. Back Musculoskelet. Rehabil.* **28**, 709–719 (2015).
24. Richardson, E. J. et al. Effects of virtual walking on spinal cord injury-related neuropathic pain: a randomized, controlled trial. *Rehabil. Psychol.* **64**, 13–24 (2019).
25. Roosink, M. et al. Interactive virtual feedback improves gait motor imagery after spinal cord injury: an exploratory study. *Restor. Neurol. Neurosci.* **34**, 227–235 (2016).
26. Villiger, M. et al. Home-based virtual reality-augmented training improves lower limb muscle strength, balance, and functional mobility following chronic incomplete spinal cord injury. *Front. Neurol.* **8**, 635 (2017).
27. Yilmaz Yelvar, G. D. et al. Is physiotherapy integrated virtual walking effective on pain, function, and kinesiophobia in patients with non-specific low-back pain? Randomised controlled trial. *Eur. Spine J.* **26**, 538–545 (2017).
28. Mintz, M. et al. Current trends in virtual exercise interventions among people with disabilities: a scoping review. *Arch. Rehabil. Res. Clin. Transl.***6**, 100373 (2024).
29. Paul, M., Bullock, K. & Bailenson, J. Virtual reality behavioral activation for adults with major depressive disorder: feasibility randomized controlled trial. *JMIR Ment. Health* **9**, e35526 (2022).
30. Li, J. et al. Effectiveness of cognitive-based interventions on psychological distress in adolescents with physical disabilities: a systematic review and meta-analysis. *Int. J. Mental Health Nur.* **33**, 1729–1742 (2024).
31. Soliman, M. M. et al. Artificial intelligence powered Metaverse: analysis, challenges and future perspectives. *Artif. Intell. Rev.* **57**, 36 (2024).
32. Saldana, D. et al. Applications of head-mounted displays for virtual reality in adult physical rehabilitation: a scoping review. *Am. J. Occup. Ther.* **74**, 7405205060p1–7405205060p15 (2020).
33. Kokkinara, E. et al. First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking. *Sci. Rep.* **6**, 28879 (2016).
34. Chen, T. et al. GestOnHMD: enabling gesture-based interaction on low-cost VR head-mounted display. *IEEE Trans. Vis. Comput. Graph.* **27**, 2597–2607 (2021).
35. Maruhn, P. VR Pedestrian simulator studies at home: comparing google cardboards to simulators in the lab and reality. *Front. Virtual Real.* **2**, https://doi.org/10.3389/frvir.2021.746971 (2021).
36. Ramachandran, V. S. & Altschuler, E. L. The use of visual feedback, in particular mirror visual feedback, in restoring brain function. *Brain* **132**, 1693–1710 (2009).
37. Ioannou, A. et al. Virtual reality and symptoms management of anxiety, depression, fatigue, and pain: a systematic review. *SAGE Open Nurs.* **6**, 2377960820936163 (2020).
38. Chen, K. et al. Virtual reality reward training for anhedonia: a pilot study. *Front Psychol.* **11**, 613617 (2020).
39. Craig, A. et al. Pain catastrophizing and negative mood states after spinal cord injury: transitioning from inpatient rehabilitation into the community. *J. Pain.* **18**, 800–810 (2017).
40. Villiger, M. et al. Relationship between structural brainstem and brain plasticity and lower-limb training in spinal cord injury: a longitudinal pilot study. *Front. Hum. Neurosci.* **9**, 254 (2015).
41. Gustin, S. M. et al. Thalamic activity and biochemical changes in individuals with neuropathic pain after spinal cord injury. *PAIN* **155**, 1027–1036 (2014).
42. Gunduz, M. E. et al. Effects of combined and alone transcranial motor cortex stimulation and mirror therapy in phantom limb pain: a randomized factorial trial. *Neurorehabil. Neural Repair* **35**, 704–716 (2021).
43. Souchet, A. D. et al. A narrative review of immersive virtual reality's ergonomics and risks at the workplace: cybersickness, visual fatigue, muscular fatigue, acute stress, and mental overload. *Virtual Real.* **27**, 19–50 (2023).
44. Javaid, A., Rasool, S. & Maqsood, A. Analysis of visual and vestibular information on motion sickness in flight simulation. *Aerospace* **11**, 139 (2024).
45. Matsuda, Y. et al. Enhancing virtual walking sensation using self-avatar in first-person perspective and foot vibrations. *Front Virtual Real.* **2**, https://doi.org/10.3389/frvir.2021.654088 (2021).
46. Groth, C. et al. Visual techniques to reduce cybersickness in virtual reality. in *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. 2021.
47. Tricco, A. C. et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. *Ann. Intern. Med.* **169**, 467–473 (2018).
48. Organization, W.H., Towards a common language for functioning, disability, and health: ICF. The international classification of functioning, disability and health, 2002.
49. Barker, T. H. et al. The revised JBI critical appraisal tool for the assessment of risk of bias for quasi-experimental studies. *JBI Evid. Synth.* **22**, 378–388 (2024).

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## Author contributions
Y.D. and Y.L. developed the research questions, designed the study, conducted the literature review, synthesized relevant findings, drafted the manuscript, and revised it. F.K.Y.W. and J.Y. assisted in the study's design and contributed to the development of research methodologies. J.L. performed data extraction and analysis and provided critical feedback on the manuscript. M.L. contributed to the development of research methodologies and manuscript revision. C.L. conducted the summary and provided expertize on the evaluation of virtual walking interventions. Y.J. synthesized relevant findings and checked the entire manuscript. Y.W. coordinated the project and edited the manuscript for clarity and consistency. All authors reviewed the manuscript.

## Competing interests
The authors declare no competing interests.

## Additional information
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