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Review

Effectiveness of virtual reality and robotic-assisted therapy for upper limb rehabilitation in spinal cord injury: a narrative review

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Abstract

Spinal cord injury is a complex neurological condition that impairs upper limb function and independence in activities of daily living. In recent years, robotic-assisted therapy and virtual reality (VR) have appeared as promising approaches in upper limb rehabilitation. This study presents a condensed narrative review of the current literature on the effectiveness of these technologies on the upper limb rehabilitation in individuals with spinal cord injury.

The findings of this review demonstrate that both robotic and VR interventions may improve motor function, strength, and functional independence in upper limbs. However, results remain inconsistent, with several studies reporting no significant differences between the study groups and suggesting that benefits may not be attributable only to technological interventions.

Overall, while these technologies appear safe and promising, further high-quality studies are required to establish their clinical effectiveness.

Keywords: Spinal cord injury; virtual reality; robotic rehabilitation; upper limb

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Introduction

Spinal cord injury (SCI) is considered to be a complex and multifaceted medical condition. Nonetheless, even with a comprehensive understanding of the anatomical and physiological aspects of the human body, the experience of individuals with SCI remains markedly distinct as it is influenced and shaped by a range of environmental factors. Individuals with SCI interact extensively with multiple components of the healthcare system, spanning from emergency medical care and surgical intervention to rehabilitation services. SCI is defined as a critical neurological disorder affecting the central nervous system. However, it subsequently gives rise to complications that affect the respiratory, cardiovascular, musculoskeletal, and genitourinary systems.

Epidemiologically, as of 2024, 15.4 million people have been recorded living with spinal cord injury.[1] In Europe, irrespective of etiology, SCI demonstrates a relatively low annual incidence estimated at 15-25 new cases per million population. The overall prevalence ranges from 300 to 1,000 individuals per million population living with the long-term consequences of SCI. In Greece, a unified national registry for individuals with SCI is currently lacking. Nevertheless, regional epidemiological data indicate an incidence of approximately 33,6 cases per million population.[2]

The International standards for Neurological Classification of spinal cord injury (ISNCSCI) established by the American spinal injury Association (ASIA) constitute the gold standard for the assessment of SCI.[3] This standardized evaluation framework determines both the neurological level of injury and the severity of impairment, thereby providing a structured protocol for clinical management, prognostication, and research applications. Within the ASIA clinical assessment, both motor and sensory functions are systematically evaluated. In the assessment of movement, the muscle strength of key muscle groups is evaluated using a numerical scale from 0 (paralysis) to 5 (normal strength). The motor level of the injury is defined as the lowest spinal level with at least muscle strength that can overcome gravity (grade ≥3), provided that all higher muscle groups are normal (grade 5). Furthermore, in the sensory assessment, 28 dermatomes are examined bilaterally using a numerical scale from 0 (absence of sensation) to 2 (normal sensation), with light touch and pinprick stimuli, using the facial area as a reference point. The lowest dermatome that retains normal sensation bilaterally defines the sensory level of the injury. Of particular importance, the assessment of sacral sparing includes the evaluation of sensory and motor function at the S4–S5 levels, determining the completeness of the injury (incomplete or complete).[4]

The loss of motor and sensory function following spinal cord injury (SCI) does not constitute merely an isolated neurological deficit; rather, it represents a primary etiological factor contributing to a wide range of systemic complications.[3] These encompass both acute and chronic conditions, including autonomic dysreflexia, neurogenic bladder and bowel dysfunction, neuropathic pain, pressure ulcers, spasticity, orthostatic hypotension, impaired thermoregulation, and sexual dysfunction.[4]

Rehabilitation after SCI is not characterized as a linear therapeutic process but as a dynamic, complex, and multifaceted intervention. Its principal objectives include ensuring patient safety, restoring functional capacity, and facilitating social reintegration. Consequently, contemporary international clinical practice advocates for the establishment of a multidisciplinary rehabilitation team, wherein healthcare professionals from diverse specialties collaborate to deliver a holistic, patient-centered approach.[1]

The rehabilitation plan is initiated during the acute phase and extends longitudinally, addressing both the direct sequelae of the injury and the individualized needs of each patient. Within this framework, interdisciplinary collaboration is of paramount importance.[5] The integration of medical management, functional retraining, nursing care, and psychological support constitutes the cornerstone for mitigating secondary complications and promoting patient autonomy and independence.[6]

Occupational therapy extends beyond the mere

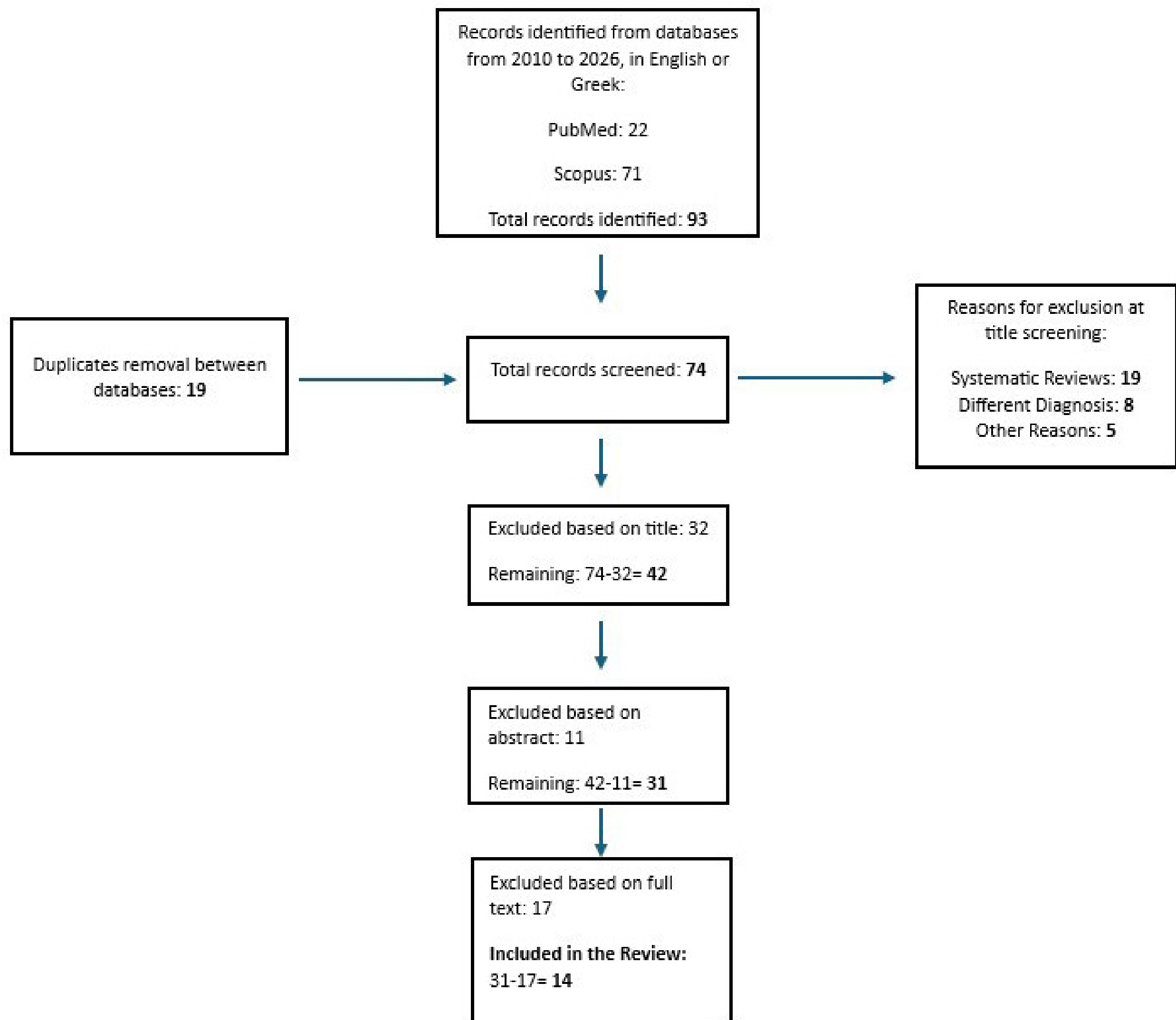

Figure 1. *Flow Diagram of Study Selection for Inclusion in the Review*

training of motor skills based on principles of motor learning. It encompasses a comprehensive assessment of the individual's functional capacity and performance in activities of daily living (ADLs). Therapeutic interventions focus on enhancing dexterity, motor coordination, and upper limb function-key components for independent living, particularly in individuals with cervical spinal cord injuries, where functional demands are significantly increased.

The incorporation of innovative technologies, such as robotic-assisted therapy and virtual reality (VR), has substantially advanced upper limb rehabilitation. These modalities enhance patient engagement, motivation, and psychological well-being, factors that are critically important in long-term rehabilitation outcomes. Their application is closely associated with the rapid evolution of neurorehabilitation and biomedical technology since the 1990s. Initially implemented in other neurological conditions, such as stroke,[6] these technologies have subsequently been adapted for use in SCI rehabilitation, to offer motor and sensory retraining, such as that of walking and upper limb function. Dozens of studies in recent years have increasingly utilized ro-

botic and virtual reality systems, aiming to provide intensive and repetitive upper limb training. Most studies have used robotic devices such as: Armeo® Spring (Hocoma AG), Armeo® Power (Hocoma AG), MAHI Exo-II (Rice University). A non- robotic, technology-assisted ReJoyce™ Rehabilitation System and interactive devices AMADEO, DIEGO, PABLO; Tyromotion were also utilized. In addition, numerous virtual reality systems have been utilized, such as: HTC Vive Virtual Reality System (HTC Corporation), Nintendo Wii® Virtual Reality Gaming System (Nintendo Co., Ltd.), Toyra® Virtual Reality System and CyberTouch™ Data Glove (Immersion Corporation), to enhance extrinsic motivation, offering measurable and objective results.

However, despite the considerable technological advancements in the field of neurorehabilitation, there still remains a lack of consensus regarding the relative efficacy of specific robotic and virtual reality systems within occupational therapy intervention protocols.

The aim of present study, as a brief literature review, was to present the current clinical research evidence on the effectiveness of integrating technological systems into occupational therapy interventions, while also considering their limitations.

Materials and Methods

An extensive literature review was conducted using the following scientific databases: PubMed/NCBI and Scopus. The keywords (mesh terms) used in the search engines of the above data bases were: spinal cord injury OR tetraplegia OR quadriplegia AND upper limb OR upper extremity OR arm function OR hand function AND virtual reality OR VR OR robotic device OR robot-assisted therapy OR exoskeleton OR telerehabilitation OR ReJoyce. The inclusion criteria comprised studies involving female/male participants over the age of sixteen years, with spinal cord injury, assessing upper-limb function, and investigating virtual reality or robotic-assisted interventions. Eligible study designs included randomized controlled trials, clinical trials, and other relevant interventional studies published from 2010 till 2026.

A total of 93 records were identified through database searching, including 71 from Scopus and 22 from PubMed. After removing 19 duplicate records, 74 studies remained for screening. During title screening, 32 studies were excluded based on irrelevance to the topic, including studies with different diagnoses, systematic reviews, and other non-relevant articles. A total of 42 studies were then assessed based on their abstracts, out of which 11 were excluded due to not meeting the inclusion criteria. Then, 31 full-text articles were evaluated for eligibility. After full-text assessment, 17 studies were excluded due to not meeting the inclusion criteria. Finally, 14 studies were included in the present review.

Discussion

Applications of virtual reality in occupational therapy for upper-limb rehabilitation

Spinal cord injury is a complex neurological condition that directly disrupts the transmission of motor and sensory signals between the brain and the peripheral nervous system. Anatomically, the spinal cord consists of ascending (sensory) and descending (motor) pathways, including the corticospinal tract, which is responsible for voluntary motor control. Damage to these neural pathways results in muscle weakness, spasticity, and functional impairment, particularly affecting the upper limbs, especially in cases of cervical injury.[4]

Currently, there is no optimal treatment of SCI patients. The foremost treatment is rehabilitation training to enhance the patient's function and quality of life, which necessitates the inclusion of occupational therapy. Conventional therapy approaches used in rehabilitation of SCI patients have demonstrated a degree of effectiveness; however, they may not fully address the complex physical and cognitive challenges associated with the injury.

In fact, VR technologies are immersive, interactive, and constructive. Through this technology, software generates an interface between the user and the computer. The main benefits provided by VR-based interventions can be presented as follows: (a) VR systems enable patients to participate in a

Table 1. Summary of Virtual Reality-Based Upper Limb Rehabilitation Studies in Spinal Cord Injury				
Author/ country	**Type of Study**	**Participants**	**Method of VR rehabilitation**	**Results**
Lim DY et al., South Korea (11)	Randomized Controlled Clinical Trial	SCI Incomplete Motor Paralysis, C4-C8	Fully Immersive VR Device HTC VIVE VR RahabWare	IG: Significant increases in grip power, lateral pinch power, and palmar pinch power (ASIA-UEMS) (p<0,05).
Prasad S. et al., India (12)	Pilot randomized, single-blinded, parallel-group trial	SCI complete/ incomplete motor paralysis, C5-C8	Non-immersive Nintendo Wii	IG: Significant improvements in upper limb function, dexterity, and independence (CUE, BBT, and SCIM-SR),(p<0.05).
Dimbwadyo-Terrer I. et al., Spain (13)	Preliminary pilot randomized controlled trial	SCI Complete Thoracic T1-T6	Semi-immersive VR and Data Glove CyberTouch	IG: Clinically meaningful improvements in motor function (MB), functional independence (SCIM, >11-point increase), self-care, dexterity (JHFT), and fine motor skills (NHPT), (p>0,05).
Dimbwadyo-Terrer I .et al., Spain (14)	Pilot Randomized Controlled Trial	SCI motor complete Cervical C5-C8	Semi-immersive VR Toyra	IG: No significant improvements in UL function (p>0,05), high satisfaction and usability scores (QUEST, satisfaction survey).

Abbreviations: ASIA-UEMS: American Spinal Injury Association – Upper Extremity Motor Score, CUE: Capabilities of Upper Extremity Questionnaire, BBT: Box and Block Test, SCIM: Spinal Cord Independence Measure, SCIM-SR: Spinal Cord Independence Measure – Self Report, MB: Motricity Index /(Motor Battery), JHFT: Jebsen Hand Function Test, NHPT: Nine Hole Peg Test, QUEST: Quebec User Evaluation of Satisfaction with Assistive Technology.

Statistical significance: $p < 0.05$ was considered statistically significant.

wide range of task-oriented motor activities within interactive and customizable environments, with adjustable levels of difficulty and repetition (b) they provide continuous, real-time feedback on performance through visual, auditory, and haptic stimuli, facilitating motor learning (c) VR interventions support the adaptability of training, including the simulation of functional activities of daily living and (d) they offer a safe, motivating, and engaging environment that promotes active participation to therapy.[7] All the above promote motor skills, sensory abilities, cognitive functions, pain management, and psychological well-being by honing their movements.

Table 2. Summary of Robotic and Technology-Assisted Upper Limb Rehabilitation Studies in Spinal Cord Injury

Author/country	Type of study	Participants	Method of Robotic Rehabilitation	Results
Vicente Lozano-Berrio et al., Spain (21)	Randomized controlled trial Interventional, Parallel group design	Cervical SCI (>C8), motor incomplete or motor complete with preservation ≥C6	Armeo Spring – passive exoskeleton	IG: Significant improvements in feeding, dressing, grooming (SCIM), and UL strength (UEMS), (p<0,05).
Loreto García-Alén et al., Spain (22)	Randomized controlled clinical trial	SCI Cervical	Armeo Power- active exoskeleton	IG & CG used Armeo Power. Significant improvements in UL function (GRASSP), dexterity (BBT), and motor scores (AIS), (p<0,05). No significant between-group differences (p>0,05).
Vicente Lozano-Berrio et al., Spain (23)	Pilot randomized controlled trial Parallel group, two-arm design	SCI Cervical C4-C8	Armeo Spring- passive exoskeleton	IG: Significant improvements in UL function (CUE) and functional independence (SCIM), (p<0,05). No between- group differences (p>0,05), except feeding (SCIM) favoring IG.
Zariffa J. et al., Canada (24)	Pilot interventional study Single group	SCI Cervical C4-C8	Armeo Spring-passive exoskeleton	Subgroup (patients with residual hand function): Significant improvement in GRASSP Sensibility in the intervention limb (p<0.05). No between-groups statistically significant differences.
Zariffa J. et al., Canada (25)	Multicenter pilot clinical study	SCI Cervical C4-C8	Armeo Spring-passive exoskeleton	Subgroup (patients with residual hand function): Significant improvement in sensory function (GRASSP) in the intervention limb (p<0,05) but not maintained. No between groups statistically significant differences.
Kim J. et al., South Korea (26)	Pilot randomized controlled trial Parallel group	SCI Cervical	Armeo Power- active exoskeleton	IG: Significant improvements in UL strength (UEMS), (p<0.05), functional independence (SCIM-III total), (p<0.05), and mobility (SCIM mobility subscale), (p<0.05).

Frullo J.M. et al., USA (30)	Controlled Trial Parallel group	SCI Cervical C3- C8	MAHI Exo-II active exoskeleton	AAN & ST used MAHI Exo-II: improvements in UL strength and sensory function over time (GRASSP Strength p<0.05), (GRASSP Sensibility p<0.05). No statistically significant differences between groups (p>0.05).
Yozbatiran N. et al., USA (31)	Randomized sham-controlled trial Parallel group	SCI Incomplete Cervical	MAHI Exo-II active exoskeleton	IG & CG used MAHI Exo-II: Improvements in UL use (MAL-AOU), motor function (UEMS), and muscle tone (MAS). No statistically significant differences between groups (p>0.05).
Kowalczewski J. et al., Canada (32)	Randomized controlled crossover trial	SCI Cervical C5-C7	Tele- Rehabilitation ReJoyce Workstation	ReJoyce Tele- Rehab: Significant improvements in hand function (ARAT), dexterity (RAHFT), and strength (Grasp/ pinch force). Significant differences favoring ReJoyce (p<0.05).
Mia Maria Kilkki et al., Finland (33)	Pilot randomized controlled crossover trial	SCI Incomplete Cervical	Technology-assisted upper rehabilitation using interactive, task-specific devices AMADEO, DIEGO, PABLO; Tyromotion with biofeedback and gamification	IG: Improvements in muscle strength (ASIA-UEMS) and goal attainment (GAS). No statistically significant differences compared to no intervention, except for UEMS (p<0.05).

Abbreviations: UEMS: Upper Extremity Motor Score, SCIM: Spinal Cord Independence Measure, GRASSP: Graded Redefined Assessment of Strength, Sensibility and Prehension, BBT: Box and Block Test, AIS: American Spinal Injury Association Impairment Scale, MAS: Modified Ashworth Scale, MAL-AOU: Motor Activity Log – Amount of Use

Statistical significance: p<0.05 was considered statistically significant.

Note: Two studies included technology-assisted, non-robotic systems (Tyromotion and ReJoyce) and were included due to their relevance to UL rehabilitation.

Applications of robotic devices in occupational therapy for upper-limb rehabilitation

The most prevalent injury is the cervical SCI. It appears to affect the 62% of the SCIs and cause severe functional impairments.[8] Injury to the cervical spinal cord affects arm and hand function to a variable extent depending on the level and severity of injury. A recent survey documented that currently over 120 devices are being developed to help rehabilitate the upper limbs of patients with neurological disorders.[9]

Robotic-assisted rehabilitation has emerged as a promising approach to upper limb dysfunction in SCI. These technologies are designed to support therapy by providing intensive and task-oriented

training, while delivering consistent and measurable therapeutic input. The main advantages given by robotic-assisted upper limb rehabilitation can be presented as follows: (a) robotic devices enable the performance of repetitive, task-specific upper limb movements at high intensity, facilitating motor relearning and functional recovery (b) they provide continuous, objective feedback on patient performance, allowing accurate monitoring of progress through measurement systems (c) robotic systems ensure consistent and standardized training, minimizing variability between therapists and (d) they offer a safe and controlled environment for therapy, while reducing the physical burden on clinicians. Collectively, these factors enhance motor recovery, functional improvement, and increase participation in activities of daily living with the aid of neuroplasticity in motor learning.[10]

Recent literature data

Virtual Reality

Four interventional studies investigating virtual reality-based systems for upper-limb rehabilitation in individuals with SCI revealed differing results. All studies used different virtual reality systems, which were the HTC Vive, Nintendo Wii, CyberTouch™ Data Glove + VR and Toyra. Some studies reported significant improvements in specific motor outcomes, such as grip strength, palmar pinch strength and lateral pinch strength, as well as functional measures (e.g., SCIM, ASIA -UEMS), particularly in the intervention groups.[11] However, most studies did not find statistically significant differences between intervention and control groups in outcome measures, including upper limb function, dexterity, and quality of life.[12_13_14] The outcome may be connected to the limited- duration intervention protocol. Prior research states that short- term interventional programs are often insufficient to reveal the advantages of virtual reality compared to conventional therapy.[15] In several cases, both intervention and control groups showed significant improvements at the post-assessment, suggesting that the observed effects may not be exclusively connected to virtual reality interventions. Due to the small sample sizes, there is insufficient evidence to support reliable scientific conclusions regarding the method's effectiveness in all four studies. At the opposite end of the spectrum, a smaller sample size, pilot randomized controlled study, reported that conventional therapy combined with VR Toyra tends to indicate improvements in functional and clinical variables.[16]

Robotic Devices

The Armeo® system (both Spring and Power devices) was the most used robotic device in the included studies. The effectiveness of this series of robotic technologies in upper limb recovery has been extensively researched in individuals with neurological conditions, such as multiple sclerosis,[17] cerebral palsy,[18] and stroke.[12-20] The included studies demonstrated improvements in motor function, muscle strength, and functional independence as reflected in outcome measures such as the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP), Action Research Arm Test (ARAT), Manual Muscle Testing (MMT), and Spinal Cord Independence Measure (SCIM).[21_22_23_24_25_26] Improvements were observed in activities of daily living, including feeding, grooming, toilet mobility, and upper-body dressing, which appear to have a positive outcome on functional performance.[21_23]

Despite within-group improvements, several studies did not report statistically significant differences between the intervention and the control group.[22_23_24_25] In many studies, both groups reported functional improvements over time, but this might not occur exclusively due to the robotic intervention.[21_22] In contrast, a systematic review and meta-analysis demonstrated that the use of robotic-assisted upper limb therapy can compete with the effectiveness of conventional therapy protocols in stroke individuals.[27] Certain studies reported improvements in specific subcategories, such as sensory function or task smoothness (GRASSP), rather than primary outcome measures, presenting variability in treatment effectiveness.[24_25]

In addition, the evidence is characterized by heterogeneity in study design, including differences in

patient populations (e.g., subacute versus chronic spinal cord injury), intervention protocols, and assessment tools.[21–24–25] Also, many of the studies have been conducted with chronic SCI patients, but evidence suggests that the most significant recovery happens in the first six months, attributed to neuroplasticity.[10–28] Some studies suggested greater benefits in patients with milder impairments or preserved residual motor function,[24–26] whereas others indicated limited or non-significant effects of Armeo®-based interventions.[22–24] These findings suggest that while Armeo® systems present an effective technology for enhancing upper limb function and promoting recovery, the evidence remains inconclusive. Similar findings have been reported in previous studies, which suggest that research in cervical SCI shows inconsistent outcomes, possibly due to the differences in therapy intensity.[29] Further high-quality randomized controlled trials are required to determine their effectiveness and to identify the populations most likely to benefit from each intervention.

In addition to Armeo® systems, other robotic-assisted approaches have been explored for upper limb rehabilitation in individuals with spinal cord injury. Including assist-as-needed training, home-based tele-rehabilitation, and combined interventions with transcranial direct current stimulation (tDCS).[30–31–32–33] Some studies demonstrated the feasibility and clinical impact of these interventions. For example, home-based technology-assisted and task-oriented rehabilitation was associated with significant improvements in upper limb function, with higher scores in ARAT and RAHFT observed in the intervention group compared to controls, with the use of ReJoyce Workstation.[32] In addition, patient-centered outcomes were highlighted in another study, where most participants (14 out of 16) reported achieving their rehabilitation goals and perceived improvements in activities of daily living, as measured by the Goal Attainment Scale (GAS).[33] A home-based rehabilitation program using the Soft Extra Muscle Glove further validates the previous findings.[34] The findings showed significant improvements in hand function, including object manipulation and grip strength, by the TRI-HFT scale. But these findings were less observed at the later follow-up assessment. Similar improvements have been reported with the use of a fabric -based soft robotic glove, demonstrated in hand function and object manipulation assessed by TRI-HFT.[35] This study was the first randomized controlled trial to investigate the effectiveness of technology -assisted device ReJoyce in the cervical SCI population, supporting improvements in upper -limb function (ARAT).[32] Despite these positive findings, such improvements were not always superior across all studies. In some cases, both intervention and control groups showed functional improvements over time, and the addition of techniques, such as tDCS combined with MAHI Exo II robotic system, did not show significant between-group differences, likely due to both groups receiving robotic rehabilitation.[30–31–33] These findings support the potential benefits of robotic-assisted therapy. Overall, the variability in intervention types, treatment protocols, and outcome measures across these studies underscores the lack of standardization in robotic rehabilitation, making it difficult to draw definitive conclusions regarding their effectiveness.

Conclusion

In conclusion, both virtual reality and robotic–assisted rehabilitation interventions appear to improve the upper limb function in individuals with spinal cord injury. These therapeutic technologies empower intensive, repetitive, and task-oriented training, while reducing the physical burden on therapists. The current evidence remains heterogeneous and inconclusive, highlighting the need for high-quality randomized controlled trials to refine intervention protocols and identify specific patient populations most likely to benefit.

Conflict of Interest

The authors declared no conflicts of interest.

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