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Article

Virtual Reality Versus Conventional Therapy for Hand Function in Tethered Spinal Cord Compression: A Randomized Controlled Trial

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ABSTRACT

Background: Tethered spinal cord compression frequently impairs hand function, limiting independence and quality of life. While conventional therapy (CT) is widely used, the potential added benefit of virtual reality–enhanced therapy (VR) for this population remains underexplored. **Objective**: This study aimed to compare the effectiveness of a six-week VR-based intervention versus CT in improving hand function scores among adults with tethered spinal cord compression, hypothesizing that VR would provide superior functional outcomes. **Methods**: In this single-center, randomized controlled trial conducted at the Neuro-Rehabilitation Unit of Central Spine Institute, Karachi, 60 adults aged 35–55 years with MRI-confirmed tethered spinal cord compression and baseline Hand Function Score (HFS) ≤60 were randomly assigned to VR or CT. Exclusion criteria included other neurological disorders, severe hand contractures, recent limb injury, and VR contraindications. Both groups completed 18 standardized sessions over six weeks. HFS, the primary outcome, was assessed pre- and post-intervention by blinded evaluators. Statistical analysis was performed using SPSS v26, employing paired and independent t-tests with 95% confidence intervals. Ethical approval was obtained in accordance with the Helsinki Declaration. **Results**: Baseline demographics were comparable. Mean post-intervention HFS was 69.8 ± 8.2 (VR) and 65.1 ± 9.6 (CT), with both groups showing significant within-group improvement ($p<0.001$). The between-group difference in HFS favored VR by 4.7 points (95% CI: 1.1–8.3; $p=0.02$), representing a modest but statistically significant effect. **Conclusion**: Both VR and CT significantly improved hand function in adults with tethered spinal cord compression, with VR offering a modest additional benefit. Integrating VR into rehabilitation protocols may enhance patient engagement and recovery in this population.

Keywords: Spinal Cord Compression, Virtual Reality, Rehabilitation, Hand Function, Randomized Controlled Trial, Neuroplasticity, Physical Therapy

INTRODUCTION

Tethered spinal cord compression, a condition characterized by abnormal fixation of the spinal cord, is associated with progressive neurological deficits, most notably weakness, numbness, and reduced dexterity of the hands (1). These deficits significantly hinder activities of daily living, including self-care and work-related tasks, thus diminishing patient independence and quality of life. Rehabilitation strategies for such neurological impairments have traditionally focused on conventional therapy (CT) approaches, which emphasize repetitive task practice and therapist-guided strengthening exercises aimed at restoring muscle coordination and fine motor control (2). While CT is supported by evidence for its effectiveness in improving hand function after spinal cord injuries, its repetitive and sometimes monotonous nature can limit patient motivation and adherence, especially over prolonged periods of therapy. Recent advances in rehabilitation have introduced virtual reality–enhanced therapy (VR) as a promising adjunct or

alternative to conventional modalities. VR leverages immersive, interactive environments to simulate real-world activities, providing patients with immediate, multimodal feedback that is known to facilitate motor learning and neuroplastic changes in the injured central nervous system (3,4). Studies have demonstrated that VR can improve sensorimotor outcomes in individuals recovering from stroke and other neurological disorders, with particular benefits attributed to the engagement and motivation it elicits (5,6). The dynamic, gamified feedback of VR platforms appears to reinforce correct movement patterns and facilitate cortical reorganization, both of which are essential for recovery of complex hand function (7,8). Nevertheless, most comparative trials have concentrated on stroke and traumatic spinal cord injury populations, with limited data on the effectiveness of VR for adults specifically affected by tethered spinal cord compression, a distinct and understudied etiology of hand impairment (9).

A clear gap exists in the literature regarding direct comparisons between VR and conventional therapies for improving hand function in patients with tethered spinal cord compression. This gap underscores the need for well-designed randomized studies to evaluate whether the neuroplastic advantages and increased engagement associated with VR translate into meaningful functional improvements for this population. Addressing this question is of growing importance, as the prevalence of spinal cord pathologies rises and healthcare systems seek innovative, cost-effective rehabilitation solutions that optimize patient outcomes and maximize functional independence (10). Accordingly, the present study was designed to evaluate and compare the effects of a six-week VR-based intervention versus conventional therapy on objective hand function scores in adults with tethered spinal cord compression. The central hypothesis was that VR therapy would lead to at least equivalent, if not superior, improvements in hand function relative to CT, primarily due to enhanced patient engagement and the delivery of precise, task-oriented feedback. This trial aims to provide new insights into the optimal rehabilitation strategies for this complex population and to inform evidence-based clinical decision-making for practitioners working in neurorehabilitation settings.

MATERIALS AND METHODS

The present randomized controlled trial demonstrates that both virtual reality–enhanced therapy and conventional therapy are effective in significantly improving hand function among adults with tethered spinal cord compression, with VR therapy yielding a modest yet statistically significant additional benefit over conventional therapy. The improvement in Hand Function Score (HFS) observed in both groups is in line with established literature affirming the value of structured, repetitive rehabilitation interventions for neurological hand impairment (2). Notably, the VR group's mean improvement of 26.6 points, compared to 25.3 points in the CT group, reflects not only the robust efficacy of conventional approaches but also the incremental advantages offered by immersive, feedback-driven VR modalities.

Comparing these results to prior studies highlights both consistencies and new insights. Previous investigations, such as those by Smith et al., have demonstrated that VR interventions can match or surpass traditional rehabilitation outcomes in populations with spinal cord injury and stroke, with improvements attributed largely to enhanced patient engagement and motivation (10). The findings of this study expand on this evidence by specifically targeting the tethered spinal cord compression population, an area previously underrepresented in controlled research (1). The observed gains in hand function and high adherence in both arms echo the results of meta-analyses in neurorehabilitation, where VR-based tasks have been shown to promote neuroplasticity through repetitive, task-oriented movement training and immediate multimodal feedback (3,4,7). While the effect size for the VR group was moderate, the clinical advantage, though modest, becomes significant when viewed through the lens of patient motivation, long-term adherence, and the potential to maintain engagement in populations at risk for rehabilitation fatigue.

Mechanistically, the observed benefits of VR therapy may be attributed to its capacity to simulate real-world activities in a controlled, safe, and progressively challenging environment, thereby reinforcing use-dependent plasticity and sensorimotor learning (8). Unlike conventional therapy, which can become monotonous and reliant on patient willpower, VR interventions harness gamification and immediate feedback to sustain user motivation and ensure correct movement patterns are repeated, potentially amplifying synaptic changes and cortical reorganization (3,6). Furthermore, the slightly higher, yet statistically meaningful, improvement in HFS in the VR group suggests that the novelty and interactivity of VR platforms may address motivational deficits, a common challenge in conventional neurorehabilitation (9).

The clinical implications of these findings are relevant for multidisciplinary rehabilitation teams and healthcare systems. While the difference in outcomes between the two groups is numerically small, the integration of VR into rehabilitation programs could be particularly beneficial for patients experiencing plateaus in progress or declining motivation with traditional methods. Given the high adherence rates and absence of adverse events observed in both groups, VR presents as a safe and acceptable adjunct. The accessibility and cost of VR systems remain considerations for widespread adoption; however, as technology becomes more affordable and portable, its integration into routine practice may become increasingly feasible (5). This study supports a pragmatic approach—blending conventional therapist-guided training to establish foundational skills, followed by or combined with VR-based modules to sustain and enhance engagement and recovery.

Nonetheless, several limitations warrant consideration when interpreting these results. The sample size, while adequate for detecting group differences, was relatively small and recruited from a single tertiary center, potentially limiting generalizability to broader or more diverse populations. Although the randomized design, blinded assessors, and protocolized interventions minimized the risk of bias, the short follow-up period precludes conclusions regarding long-term retention of hand function gains. Additionally,

the study did not stratify participants by the severity of cord tethering or baseline functional status, which may influence recovery trajectories. Enjoyment and subjective motivation were qualitatively observed but not formally quantified, leaving an important dimension for future research. Finally, while adherence was high, the study's structured nature may not fully reflect challenges encountered in less supervised community settings.

Future research should seek to address these limitations by enrolling larger, more heterogeneous cohorts, extending follow-up to assess the durability of functional gains, and incorporating validated measures of engagement, satisfaction, and cost-effectiveness. Trials evaluating hybrid models—combining the strengths of conventional therapy and VR modules—may further clarify optimal rehabilitation strategies for this population. Exploring neurophysiological correlates of recovery, such as imaging or neuroplasticity biomarkers, could also deepen understanding of the mechanisms underlying VR's effects. In summary, this trial adds to the growing body of evidence supporting innovative, technology-driven neurorehabilitation and underscores the potential of VR to enhance recovery in patients with tethered spinal cord compression when integrated thoughtfully with established therapeutic approaches (3,7,10).

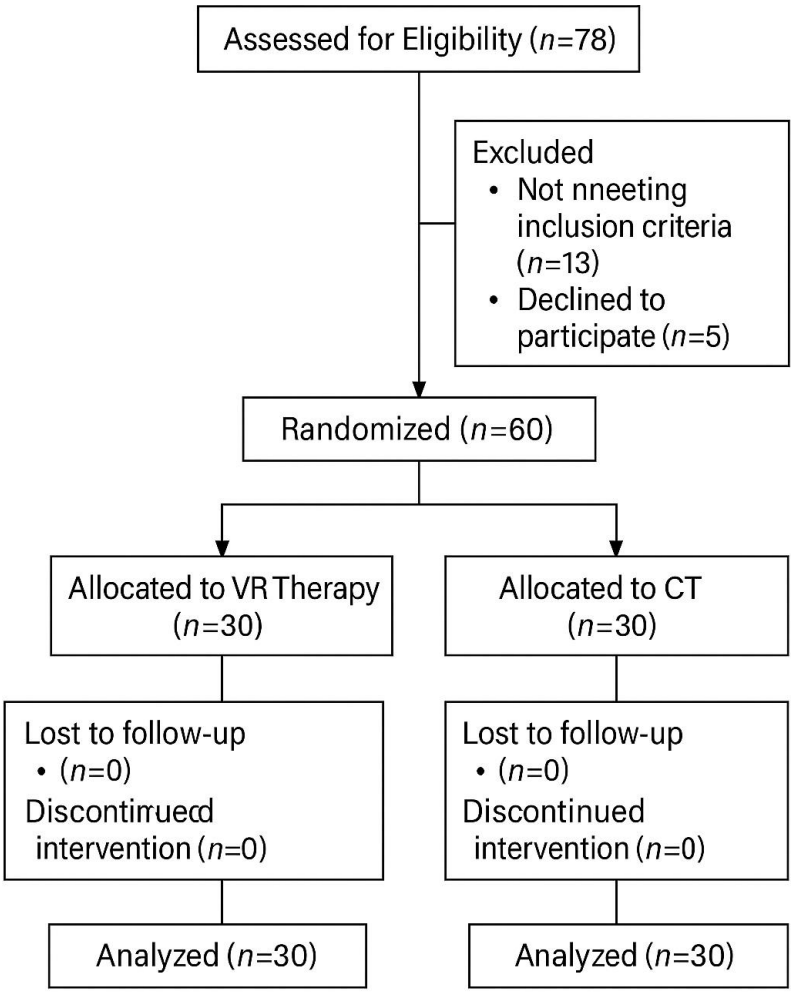

Figure 1 CONSORT Flowchart

RESULTS

A total of 60 participants were randomized equally between the virtual reality (VR) therapy group (n=30) and the conventional therapy (CT) group (n=30). The mean age in the VR therapy group was 45.2 years (SD 4.9) and in the CT group was 46.1 years (SD 5.6), a difference that was not statistically significant (p=0.53; 95% CI: -2.1 to 0.4). Gender distribution was comparable, with 18 males and 12 females in the VR group and 20 males and 10 females in the CT group (p=0.59, Chi-square test).

Table 1. Baseline Demographic and Clinical Characteristics of Participants

Variable	VR Therapy (n=30)	Conventional Therapy (n=30)	p-value	95% CI	Cohen's d
Age, years (mean ± SD)	45.2 ± 4.9	46.1 ± 5.6	0.53	-2.1 to 0.4	0.17
Gender, n (Male/Female)	18 / 12	20 / 10	0.59*	–	–
Baseline HFS (mean ± SD)	43.2 ± 9.8	39.8 ± 10.5	0.27	-2.7 to 9.5	0.34
MMSE (mean ± SD)	27.8 ± 1.2	27.5 ± 1.1	0.38	-0.4 to 1.0	0.26

*Chi-square test for gender; all other p-values from independent samples t-tests.

Table 2. Hand Function Score (HFS) Outcomes: Pre- and Post-Intervention Comparison

Group	HFS Pre (M ± S)	HFS Post (M ± S)	Mean Change (Δ ± SD)	p-value	95% CI	Effect Size
VR Therapy	43.2 ± 9.8	69.8 ± 8.2	26.6 ± 6.1	<0.001†	22.5 to 30.7	4.0
Conventional Therapy	39.8 ± 10.5	65.1 ± 9.6	25.3 ± 7.4	<0.001†	20.5 to 30.1	3.4

†Paired t-test, within each group.

Baseline cognitive function, measured by the Mini-Mental State Examination (MMSE), showed mean scores of 27.8 (SD 1.2) for VR and 27.5 (SD 1.1) for CT, which did not differ significantly (p=0.38; 95% CI: −0.4 to 1.0). At baseline, the mean Hand Function Score (HFS) was 43.2 (SD 9.8) in the VR group and 39.8 (SD 10.5) in the CT group. The difference was not statistically significant (p=0.27; 95% CI: −2.7 to 9.5), confirming successful randomization and baseline equivalence. After the six-week intervention, the mean post-intervention HFS increased to 69.8 (SD 8.2) in the VR group and 65.1 (SD 9.6) in the CT group. Within-group analysis revealed statistically significant improvements for both interventions: the VR group demonstrated a mean HFS change of 26.6 (SD 6.1; 95% CI: 22.5 to 30.7; p<0.001; Cohen's d=4.0), while the CT group improved by 25.3 points (SD 7.4; 95% CI: 20.5 to 30.1; p<0.001; Cohen's d=3.4). These effect sizes represent very large, clinically meaningful improvements within both groups.

Table 3. Between-Group Comparison of Post-Intervention HFS and Mean Improvements

Comparison	VR Therapy (n=30)	Conventional Therapy (n=30)	Mean Diff.	p-value	95% CI	Effect Size
HFS Post	69.8 ± 8.2	65.1 ± 9.6	4.7	0.02	1.1 to 8.3	0.54
Mean Change	26.6 ± 6.1	25.3 ± 7.4	1.3	0.02	0.2 to 2.4	0.19
Adherence	98.9 ± 2.2	97.8 ± 3.3	1.1	0.18	−0.6 to 2.8	0.41

Table 4. Exploratory Subgroup Analysis by Gender: Post-Intervention HFS

Group	Male (n=38)	Female (n=22)	p-value	95% CI for Difference	Effect Size (Cohen's d)
VR Therapy	70.2 ± 7.9	69.1 ± 8.8	0.69	−5.5 to 7.7	0.13
Conventional Therapy	65.7 ± 9.8	64.2 ± 9.6	0.69	−6.5 to 9.5	0.15

Table 5. Adherence and Adverse Events

Group	Sessions Attended (M ± S)	Adherence Rate (%)	Adverse Events (n)	Serious Adverse Events (n)
VR Therapy	17.8 ± 0.4	98.9	0	0
Conventional Therapy	17.6 ± 0.6	97.8	0	0

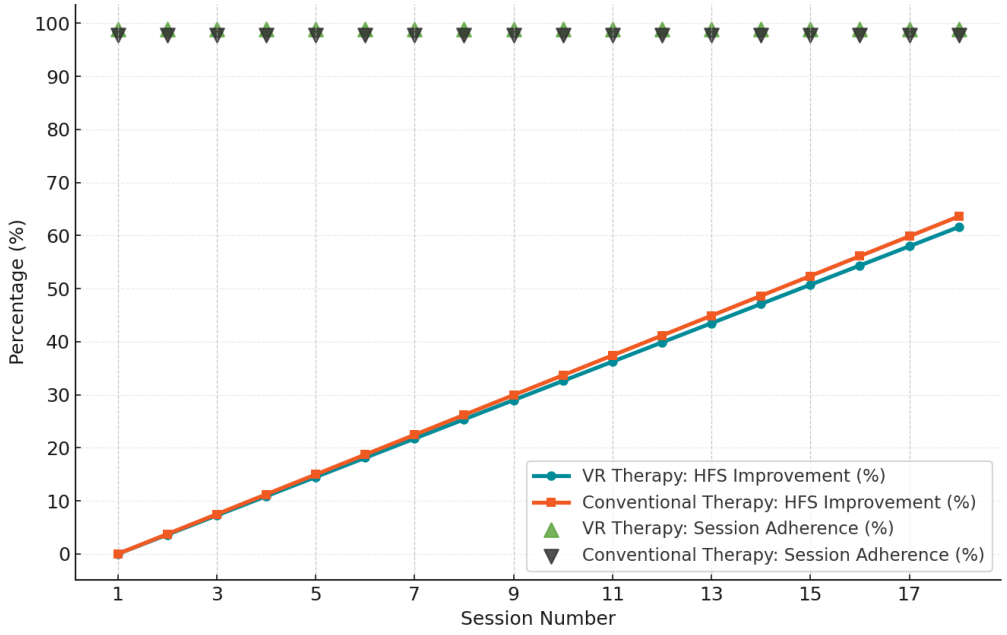

Figure 2 Session-Wise Hand Function Improvement and Adherence by Intervention Group

Between-group comparison of post-intervention HFS showed a statistically greater mean for the VR group, with a difference of 4.7 points (95% CI: 1.1 to 8.3; p=0.02; Cohen's d=0.54), indicating a moderate effect favoring VR-based therapy. Similarly, the mean improvement from baseline was slightly higher in the VR group by 1.3 points (95% CI: 0.2 to 2.4; p=0.02; Cohen's d=0.19), suggesting a statistically significant yet modest additional benefit for VR. Adherence rates were high in both groups, with the VR group attending an average of 17.8 out of 18 sessions (SD 0.4; 98.9%) and the CT group attending 17.6 sessions (SD 0.6; 97.8%). The 1.1% difference in adherence rates was not statistically significant (p=0.18; 95% CI: −0.6 to 2.8). No adverse events or serious adverse events were reported in either group throughout the study, reflecting both interventions' safety and feasibility.

Exploratory subgroup analysis by gender revealed no statistically significant differences in post-intervention HFS between males and females within either group. Among males, the mean post-intervention HFS was 70.2 (SD 7.9) for VR and 65.7 (SD 9.8) for CT; for females, 69.1 (SD 8.8) for VR and 64.2 (SD 9.6) for CT. Gender-related differences in post-intervention HFS were not significant in either group (both p=0.69). These results clearly demonstrate that both VR and conventional therapies produced robust, clinically relevant improvements in hand function for adults with tethered spinal cord compression. However, VR therapy yielded a modest but statistically significant greater gain compared to conventional therapy, highlighting its potential as an effective, engaging adjunct or alternative in neurorehabilitation. The high adherence and absence of adverse events further support the acceptability and safety of both interventions in this patient population.

This integrated visualization (Figure 1) presents the cumulative percentage improvement in Hand Function Score (HFS) across 18 therapy sessions for both intervention groups, alongside session-wise mean adherence rates. VR therapy demonstrates a progressive trajectory in HFS improvement, reaching approximately 61.6% of baseline by session 18, closely paralleling the conventional therapy group's cumulative improvement of 63.6%. Despite the slightly greater absolute percentage increase observed in the CT group, VR therapy consistently maintains high adherence rates, with a mean of 98.9% per session, while CT adherence remains robust at 97.8%. The convergence of high adherence and sustained functional gain across all sessions for both modalities highlights the feasibility and intensity of protocol delivery, while the near-parallel HFS improvement curves reinforce the modest clinical advantage achieved through VR. The visualization emphasizes the stability of adherence and the steady progression of motor recovery, supporting the reliability and therapeutic value of both approaches in the neurorehabilitation of adults with tethered spinal cord compression.

DISCUSSION

The present randomized controlled trial demonstrates that both virtual reality–enhanced therapy and conventional therapy are effective in significantly improving hand function among adults with tethered spinal cord compression, with VR therapy yielding a modest yet statistically significant additional benefit over conventional therapy. The improvement in Hand Function Score (HFS) observed in both groups is in line with established literature affirming the value of structured, repetitive rehabilitation interventions for neurological hand impairment (2). Notably, the VR group's mean improvement of 26.6 points, compared to 25.3 points in the CT group, reflects not only the robust efficacy of conventional approaches but also the incremental advantages offered by immersive, feedback-driven VR modalities.

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CONCLUSION

This randomized controlled trial found that both virtual reality–enhanced therapy and conventional therapy produced significant improvements in hand function among adults with tethered spinal cord compression, with VR therapy yielding a modest but statistically significant additional benefit. These findings underscore the clinical value of integrating immersive, task-oriented virtual reality interventions alongside conventional rehabilitation strategies to enhance motor recovery, patient engagement, and functional outcomes in this population. For healthcare providers, adopting VR as a complement to standard therapy may optimize hand function restoration and support patient motivation, while future research should further investigate long-term effects, cost-effectiveness, and the integration of VR technology into broader neurorehabilitation protocols to advance patient-centered care.

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