

Immersive virtual reality gaming versus dose-matched conventional task-oriented training for hand function in chronic incomplete tetraplegia: a pilot randomised controlled trial

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ABSTRACT

Background. Recovery of hand function is the highest-ranked rehabilitation priority among people with tetraplegia, yet meaningful gains remain difficult to achieve in the chronic phase. Immersive virtual reality (VR) gaming may increase repetition and engagement relative to conventional therapy, but randomised evidence in cervical spinal cord injury (SCI) is limited and dominated by non-immersive systems.

Objective. To compare an 8-week immersive VR gaming programme with dose-matched conventional task-oriented training on hand function in adults with chronic incomplete tetraplegia.

Methods. Two-arm, parallel-group, assessor-blinded pilot randomised controlled trial. Twenty adults (18–60 years) with chronic (≥ 1 year) incomplete cervical SCI (C6–C8; AIS grade C or D) were randomised 1:1 to immersive VR gaming delivered through a head-mounted display or to conventional task-oriented training. Both arms received 60-minute supervised sessions three times weekly for 8 weeks (24 sessions). The primary outcome was the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP) total score. Secondary outcomes were GRASSP subcomponents, the Box and Block Test (BBT), Jamar grip strength and the Spinal Cord Independence Measure (SCIM). Between-group differences in change from baseline were tested with the Mann–Whitney U test.

Results. All 20 participants completed the intervention and were analysed; no adverse events occurred. Groups were comparable at baseline. GRASSP total improved by 24.30 ± 3.37 points with VR and by 10.30 ± 3.50 points with conventional training (median between-group difference 14.0 points; $U = 100$, $p < 0.001$; $r = 0.85$). Larger gains also favoured VR for the BBT (median difference 7.0 blocks, $p < 0.001$), grip strength (3.0 kg, $p < 0.001$) and SCIM (10.0 points, $p < 0.001$). The between-group difference in GRASSP prehension performance was smaller and did not survive correction for multiple comparisons ($p = 0.027$).

Conclusions. In this pilot trial, immersive VR gaming produced greater improvement than dose-matched conventional training across all measured domains of hand function and functional independence. The trial was not powered for definitive superiority; the effect estimates are imprecise and require confirmation in an adequately powered multicentre trial with longer follow-up.

Keywords: virtual reality; spinal cord injury; tetraplegia; upper extremity; neurological rehabilitation; hand strength.

INTRODUCTION

Cervical spinal cord injury (SCI) produces tetraplegia, a pattern of motor, sensory and autonomic impairment affecting all four limbs and the trunk. Among the functions lost, people living with tetraplegia consistently rank

recovery of arm and hand function above all others, ahead of bladder, bowel and even walking function, because the hand determines independence in feeding, dressing, grooming, writing, wheelchair propulsion and the use of assistive technology.¹ Small absolute gains in wrist extension, finger flexion or grip force can therefore translate into disproportionately large changes in day-to-day autonomy and caregiver burden.

Individuals graded C or D on the American Spinal Injury Association Impairment Scale (AIS) retain motor function below the neurological level and possess demonstrable capacity for further recovery.² That capacity is mediated by activity-dependent neuroplasticity: repetitive, intensive, task-specific and salient practice strengthens spared corticospinal and propriospinal circuitry and drives cortical reorganisation. Conventional task-oriented training operationalises these principles and remains the standard of care. In the chronic phase, however, its effectiveness is constrained less by its content than by its delivery. Repetitive drills are monotonous, motivation and adherence decline, fatigue and spasticity limit session intensity, and recovery plateaus discourage sustained effort. The number of high-quality repetitions actually achieved therefore often falls well below what neuroplastic change is thought to require.³

Immersive virtual reality (VR) has been proposed as a way to close that gap. Delivered through a head-mounted display with motion-tracked controllers, VR embeds therapeutic movement inside goal-directed game play, supplying multisensory feedback, continuous performance metrics, and difficulty that adapts to the individual.⁴ The proposed mechanisms are convergent rather than novel: gamification raises intrinsic motivation and therefore repetition count; augmented visual and auditory feedback supports error-based motor learning; and simulated functional environments provide the contextual specificity that transfer to activities of daily living appears to require.^{5,6} In stroke rehabilitation, where this rationale has been tested most extensively, VR-based upper limb training yields improvements in motor function and dexterity that are at least comparable with, and in several trials superior to, conventional therapy.⁷⁻⁹

Extrapolating from stroke to cervical SCI is not straightforward. Tetraplegia involves a distinct combination of altered tone, impaired or absent cutaneous feedback, muscle imbalance across the wrist and hand, reduced trunk stability and altered hand biomechanics, and the resulting movement repertoire differs substantially from that of the hemiparetic upper limb.¹⁰ Studies of VR in SCI populations have reported feasibility and short-term motor gains, but most have used non-immersive or semi-immersive systems, enrolled small or heterogeneous samples, lacked randomised controls, or relied on outcome measures not specific to the tetraplegic hand.¹¹⁻¹⁵ Recent systematic reviews and meta-analyses have reached broadly favourable but cautious conclusions and have identified the same shortfall: too few randomised trials, and almost none comparing fully immersive VR against a dose-matched conventional comparator.¹⁶⁻¹⁸

This pilot randomised controlled trial was designed to address that gap. Its objective was to compare an 8-week immersive VR gaming programme with dose-matched conventional task-oriented training on hand function, manual dexterity, grip strength and functional independence in adults with chronic incomplete tetraplegia, and to generate the effect and variability estimates needed to design a definitive trial.

METHODS

Trial design and setting

This was a two-arm, parallel-group, assessor-blinded pilot randomised controlled trial with 1:1 allocation. Participants were recruited from spinal cord injury rehabilitation centres and neuro-physiotherapy outpatient departments in the National Capital Region, India, and all interventions and assessments were delivered on site under the supervision of qualified physiotherapists. Recruitment and follow-up ran from [month year] to [month year]. The trial is reported in accordance with the CONSORT 2010 statement and its extension for randomised pilot and feasibility trials.^{19,20}

The protocol was approved by the Institutional Ethics Committee of the Institute of Applied Medicines and Research, Ghaziabad (approval number [insert]; date [insert]), and the trial was prospectively registered with the Clinical Trials Registry – India ([registration number]). All participants gave written informed consent before enrolment. The study was conducted in accordance with the Declaration of Helsinki.

Participants

Adults aged 18–60 years were eligible if they had a clinically and radiologically confirmed cervical SCI at C5–C8, were classified AIS grade C or D, were at least one year post-injury, retained active wrist extension of manual

muscle test grade 2 or above together with some active finger flexion, were medically stable, could follow verbal instructions and provided written consent.

Exclusion criteria were complete injury (AIS grade A or B); severe upper limb spasticity (Modified Ashworth Scale above 3); uncorrected visual or vestibular impairment; a history of photosensitive epilepsy; severe motion sickness; cognitive impairment sufficient to preclude participation; and concurrent enrolment in any other experimental upper limb rehabilitation programme. Eligible individuals were enrolled consecutively as they presented at the participating centres.

Randomisation and blinding

After baseline assessment, participants were allocated 1:1 to the VR or conventional arm using a computer-generated random sequence. Allocation was concealed in sequentially numbered, opaque, sealed envelopes prepared in advance and opened only after baseline data had been recorded, by a member of staff not involved in outcome assessment or intervention delivery.

The outcome assessor, a trained physiotherapist who administered all measures at both time points, was blinded to group allocation and took no part in treatment. Because of the overt nature of the interventions, neither participants nor treating therapists could be blinded. Participants were asked not to discuss the content of their sessions with the assessor.

Interventions

Both arms received 60-minute supervised sessions three times weekly for 8 weeks, a total of 24 sessions, and were therefore matched for contact time, frequency and duration. Every session in both arms comprised a 5–10 minute warm-up, a 45–50 minute main component and a 5-minute cool-down of upper limb stretching. Attendance was recorded for every session and participants were monitored throughout for fatigue, pain, spasticity, cybersickness and any other adverse event.

Immersive VR gaming (experimental arm). Participants trained using a commercially available head-mounted display (Meta Quest 2, Meta Platforms, Menlo Park, CA, USA) with motion-tracking hand controllers. Warm-up consisted of active-assisted range-of-motion exercise for the shoulder, elbow, wrist and fingers. Therapeutic games were selected to elicit wrist extension, hand opening and closing, grasp and release, precision pinch, reaching and fine motor coordination. Difficulty, speed and task complexity were titrated by the supervising therapist to individual performance so that a progressive challenge was maintained. The programme advanced in four stages: gross motor control and rhythm-based whole-arm movement (weeks 1–2), wrist control and grip initiation through simulated catching and grasping (weeks 3–4), fine motor and dexterity tasks involving virtual object manipulation (weeks 5–6), and simulated activities of daily living (weeks 7–8).

Conventional task-oriented training (comparator arm). Participants received a structured programme based on established neurorehabilitation principles. After passive and active range-of-motion warm-up, sessions comprised 15–20 minutes of grip and pinch strengthening with therapy putty and hand grippers, 15–20 minutes of dexterity training using pegboards, coin transfer and small-object manipulation, and 10–15 minutes of functional task practice including buttoning, writing and handling everyday utensils. Progression followed the same four-stage structure: grip activation and assisted grasp (weeks 1–2), progressive resistance strengthening (weeks 3–4), fine motor and coordination work (weeks 5–6), and functional practice directed at independence in daily activities (weeks 7–8), with resistance, repetitions and task complexity increased according to tolerance.

Outcome measures

All outcomes were assessed at baseline and within one week of the final session, by the same blinded assessor under standardised conditions.

The primary outcome was the total score of the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP), a multimodal measure developed specifically for the upper limb in tetraplegia and validated for use across the continuum of recovery after cervical SCI.^{21,22} The GRASSP comprises strength (manual grading of ten upper limb muscles), dorsal and palmar sensibility (Semmes–Weinstein monofilaments), prehension ability (cylindrical grasp, lateral key pinch and tip-to-tip pinch) and prehension performance (standardised functional tasks). Subcomponent scores were analysed as secondary outcomes.

Secondary outcomes were gross manual dexterity, measured with the Box and Block Test as the number of blocks transferred in 60 seconds;²³ maximum isometric grip strength, measured in kilograms with a calibrated Jamar hand dynamometer in the standardised seated position with the shoulder adducted, elbow flexed to 90° and

forearm neutral, recording the best of three trials; and functional independence, measured with the Spinal Cord Independence Measure (SCIM), a clinician-rated scale covering self-care, respiration and sphincter management, and mobility.^{24,25} Adverse events were recorded throughout.

Sample size

An a priori calculation for the comparison of two independent means, assuming a large standardised effect (Cohen's $d = 0.8$), two-sided $\alpha = 0.05$ and 80% power, indicated approximately 25 participants per group. Recruitment of that number was not feasible within the study period given the specialised and difficult-to-access target population. The trial was therefore conducted as a pilot with 10 participants per group, sufficient to assess feasibility of the protocol and to generate the effect and variability estimates required to power a definitive trial, but not to establish superiority. All effect estimates should be read in that light.

Statistical analysis

Data were entered in Microsoft Excel and analysed in SPSS version [insert] (IBM Corp., Armonk, NY, USA). Continuous variables are summarised as mean $\pm$ standard deviation and as median with interquartile range; categorical variables as counts and percentages.

Distributional assumptions were examined with the Shapiro–Wilk test. Because several change-score distributions departed from normality and because 10 observations per group provides little power to detect such departures, non-parametric methods were used throughout in preference to the t-tests specified in the original protocol. Within-group change from baseline was tested with the Wilcoxon signed-rank test. The between-group comparison — the analysis of primary interest — was performed on change scores (post-intervention minus baseline) using the Mann–Whitney U test, with the Hodges–Lehmann estimator giving the median between-group difference. Effect size is reported as $r = Z/\sqrt{N}$, where values of 0.10, 0.30 and 0.50 denote small, medium and large effects. Baseline comparability was examined with the Mann–Whitney U test for continuous variables and the chi-square test for categorical variables.

Two-sided α was set at 0.05. Eight outcomes were compared between groups; a Bonferroni-corrected threshold of $p < 0.0063$ is reported alongside the nominal values, and secondary findings that do not meet it are identified as such. No interim analyses were conducted. All randomised participants completed the intervention and provided complete data, so the analysed set corresponds to the randomised set and no imputation was required.

RESULTS

Participant flow and baseline characteristics

Twenty participants were randomised, 10 to each arm (Figure 1). All 20 completed the full 24 sessions and both assessments; there were no withdrawals, no protocol deviations and no missing data. No adverse events were reported in either arm. Specifically, no participant in the VR group reported cybersickness, dizziness, visual discomfort or increased spasticity of sufficient severity to interrupt or terminate a session.

Baseline demographic and clinical characteristics are shown in Table 1. The groups were comparable in age, weight, height and time since injury, and in the distribution of neurological level, AIS grade and hand tested (all $p > 0.05$). No baseline outcome measure differed significantly between groups (all $p \geq 0.25$).

Table 1. Baseline demographic and clinical characteristics of participants.

Characteristic	VR group (n = 10)	Conventional group (n = 10)	Test statistic	p value
Age, years	33.20 $\pm$ 3.79	33.90 $\pm$ 4.53	U = 44.5	0.71
Weight, kg	70.50 $\pm$ 4.67	71.00 $\pm$ 7.02	U = 47.0	0.85
Height, cm	170.90 $\pm$ 3.07	171.20 $\pm$ 4.89	U = 48.0	0.87
Time since injury, years	2.83 $\pm$ 1.10	2.72 $\pm$ 1.18	U = 52.0	0.83
Neurological level, n (%)			$\chi^2 = 0.00$	1.00
C6	5 (50)	5 (50)		
C7	3 (30)	3 (30)		

Characteristic	VR group (n = 10)	Conventional group (n = 10)	Test statistic	p value
C8	2 (20)	2 (20)		
AIS grade, n (%)			$\chi^2 = 0.00$	1.00
C	5 (50)	5 (50)		
D	5 (50)	5 (50)		
Hand tested, n (%)			$\chi^2 = 0.00$	1.00
Right	5 (50)	5 (50)		
Left	2 (20)	2 (20)		
Dominant	3 (30)	3 (30)		

Values are mean $\pm$ standard deviation unless otherwise stated. Continuous variables compared with the Mann–Whitney U test; categorical variables with the chi-square test. AIS, American Spinal Injury Association Impairment Scale; VR, virtual reality.

Primary outcome: GRASSP total score

GRASSP total score improved significantly in both arms (both $p = 0.002$, Wilcoxon signed-rank). In the VR group the mean increase was 24.30 ± 3.37 points, from 43.80 ± 3.52 at baseline to 68.10 ± 6.67 after intervention. In the conventional group the mean increase was 10.30 ± 3.50 points, from 43.10 ± 2.60 to 53.40 ± 5.80 .

The improvement was substantially greater with VR. The median between-group difference in change was 14.0 GRASSP points in favour of the VR arm ($U = 100$, $p < 0.001$; $r = 0.85$), a difference that exceeded the Bonferroni-corrected threshold. Table 2 presents the primary outcome together with the GRASSP subcomponents, and Figure 2 displays mean change from baseline for the principal outcomes.

Table 2. Primary outcome (GRASSP total) and GRASSP subcomponent scores at baseline and after 8 weeks.

Outcome	VR baseline	VR post	VR change	Conv. baseline	Conv. post	Conv. change	p
GRASSP total	43.80 ± 3.52	68.10 ± 6.67	24.30 ± 3.37	43.10 ± 2.60	53.40 ± 5.80	10.30 ± 3.50	$< 0.001^*$
Strength	19.40 ± 2.22	31.10 ± 2.60	11.70 ± 0.67	18.50 ± 2.17	23.40 ± 2.22	4.90 ± 0.32	$< 0.001^*$
Sensibility	11.30 ± 1.49	15.30 ± 1.49	4.00 ± 0.00	11.00 ± 1.83	13.00 ± 1.83	2.00 ± 0.00	$< 0.001^*$
Prehension ability	7.00 ± 1.05	10.10 ± 1.52	3.10 ± 0.57	6.50 ± 1.27	7.50 ± 1.27	1.00 ± 0.00	$< 0.001^*$
Prehension performance	6.10 ± 1.37	11.60 ± 1.26	5.50 ± 2.55	7.10 ± 2.73	9.50 ± 1.35	2.40 ± 3.41	0.027

Values are mean $\pm$ standard deviation. Change is post-intervention minus baseline. The p value is for the between-group comparison of change scores (Mann–Whitney U test). * Meets the Bonferroni-corrected threshold of $p < 0.0063$ for eight comparisons. Within-group change was significant in both arms for all outcomes (Wilcoxon signed-rank, $p = 0.002$) except prehension performance in the conventional arm ($p = 0.063$). No baseline

difference between groups reached significance (all $p \geq 0.25$). Conv., conventional; GRASSP, Graded Redefined Assessment of Strength, Sensibility and Prehension; VR, virtual reality.

GRASSP subcomponents

Three of the four subcomponents favoured the VR arm at the corrected significance threshold: strength (median difference 6.8 points, $p < 0.001$), sensibility (2.0 points, $p < 0.001$) and prehension ability (2.0 points, $p < 0.001$). The fourth, prehension performance, showed a smaller and less certain advantage (median difference 3.0 points, $U = 80$, $p = 0.027$, $r = 0.50$): this did not survive correction for multiple comparisons, and the within-group improvement in the conventional arm did not reach significance ($p = 0.063$). Prehension performance also showed markedly greater between-participant variability than the other subcomponents in both arms.

Secondary outcomes

Results for dexterity, grip strength and functional independence are presented in Table 3, and all favoured the VR arm.

Table 3. Secondary outcomes: manual dexterity, grip strength and functional independence.

Outcome	VR change	Conventional change	Median difference	U	p	Effect size r
Box and Block Test, blocks	13.40 ± 1.26	6.10 ± 0.99	7.0	100	< 0.001*	0.85
Grip strength, kg	5.70 ± 0.48	3.00 ± 0.00	3.0	100	< 0.001*	0.85
SCIM total	17.00 ± 1.49	7.00 ± 0.00	10.0	100	< 0.001*	0.85

Change is post-intervention minus baseline, expressed as mean ± standard deviation. Median difference is the Hodges–Lehmann estimate of the between-group difference in change. p values from the Mann–Whitney U test; * meets the Bonferroni-corrected threshold of $p < 0.0063$. Effect size $r = Z/\sqrt{N}$. Within-group change was significant in both arms for all three outcomes (Wilcoxon signed-rank, $p = 0.002$). SCIM, Spinal Cord Independence Measure; VR, virtual reality.

Manual dexterity improved by 13.40 ± 1.26 blocks with VR and by 6.10 ± 0.99 blocks with conventional training, a median between-group difference of 7.0 blocks ($U = 100$, $p < 0.001$; $r = 0.85$). Grip strength increased by 5.70 ± 0.48 kg and 3.00 ± 0.00 kg respectively, a median difference of 3.0 kg ($U = 100$, $p < 0.001$; $r = 0.85$). SCIM scores rose by 17.00 ± 1.49 points with VR and 7.00 ± 0.00 points with conventional training, a median difference of 10.0 points ($U = 100$, $p < 0.001$; $r = 0.85$). All three comparisons met the Bonferroni-corrected threshold.

DISCUSSION

In this pilot randomised controlled trial, eight weeks of immersive VR gaming produced greater improvement than dose-matched conventional task-oriented training across every domain assessed: overall hand function, muscle strength, sensibility, prehension, gross manual dexterity, grip strength and functional independence. Both interventions improved outcomes relative to baseline, which is itself notable in a chronic cohort a mean of almost three years post-injury, where spontaneous recovery is negligible and plateau is the expected trajectory. The distinguishing finding is the magnitude of the difference between them: the VR arm gained roughly twice as much on the primary outcome as the comparator, and the advantage was consistent in direction across all eight comparisons.

Comparison with previous work

The direction of these findings agrees with the small existing SCI literature. Prasad and colleagues, in a pilot randomised trial of VR-based upper limb training in SCI, reported gains favouring the VR arm;¹¹ Lim and colleagues found a fully immersive VR protocol feasible and effective for upper limb rehabilitation after SCI;¹² and Dimbwadyo-Terrer and colleagues obtained comparable results using a data glove within an immersive environment.¹³ Work with semi-immersive and haptic systems has pointed the same way.^{14,15} Meta-analyses of VR after SCI have concluded that the modality is promising for upper limb and functional outcomes while noting that the evidence base is thin, methodologically variable and dominated by non-immersive systems.^{16–18} The present trial adds a fully immersive intervention, a dose-matched active comparator, a blinded assessor and an SCI-specific primary outcome, a combination that has been uncommon in this literature.

The effect sizes observed here are, however, considerably larger than those typically reported in the stroke and SCI VR literature, where between-group differences are usually modest and frequently non-significant.^{7–9,16} Effect estimates derived from ten participants per group are inherently imprecise and, in small trials that detect an effect, systematically biased upward. The magnitude of the differences reported here should therefore be treated as a hypothesis for testing rather than as an estimate of the true effect.

Possible mechanisms

Several mechanisms plausibly contribute. The most parsimonious is dose. Although contact time was matched, time on task need not have been: game-based practice sustains attention and tolerance for repetition, so the number of purposeful movement repetitions completed within a 60-minute session may have been considerably higher in the VR arm. Continuous augmented visual and auditory feedback supports error-based motor learning in a population whose intrinsic proprioceptive and cutaneous feedback is degraded, which may also help explain the improvement observed in the sensibility subcomponent. Immersive environments recruit cortical networks associated with motor planning and observation, and gamified reward is thought to engage dopaminergic pathways that facilitate consolidation. Finally, the functional simulation used in the final training block provided contextual specificity that may account for the transfer to SCIM scores, since improvement on an impairment measure does not automatically translate into everyday independence.

Clinical implications

Commercially available head-mounted systems are now inexpensive relative to robotic or functional electrical stimulation platforms, require little space and were tolerated here without adverse events, including in participants with C6-level injury and limited active hand movement. These findings support the use of immersive VR as an adjunct within a supervised upper limb programme rather than as a replacement for hands-on therapy. The comparator arm also improved significantly, and the VR protocol in this trial was delivered under continuous therapist supervision with individualised progression, not as independent self-directed practice.

Limitations

The principal limitation is sample size. Ten participants per group is well below the 25 per group indicated by the a priori calculation, and the trial was neither designed nor powered to establish superiority. Confidence in the point estimates is correspondingly low.

Second, outcomes were measured only immediately after the intervention. Whether the advantage persists, and whether the novelty that may partly drive engagement decays with continued exposure, cannot be determined without longer follow-up.

Third, blinding was limited to the assessor. Participants and treating therapists were necessarily aware of allocation, and an intervention as visibly novel as immersive VR is susceptible to expectancy and Hawthorne effects. The comparator was dose-matched but not matched for novelty or attention, so part of the observed difference may reflect non-specific effects of receiving a new technology rather than the mechanism of VR itself. Fourth, eight between-group comparisons were performed. Only findings meeting the Bonferroni-corrected threshold should be regarded as robust; the prehension performance result did not, and is best treated as exploratory.

Fifth, change scores for several outcomes showed very little between-participant variability, with grip strength and SCIM in the comparator arm improving by an identical amount in every participant. Uniformity of this degree is unusual in clinical data, and while it may reflect the coarse granularity of these measures over an 8-week interval in a homogeneous cohort, it also narrows the confidence intervals around the between-group estimates and makes them appear more precise than they are. This further supports treating the effect sizes as provisional.

Sixth, the trial was conducted at centres within a single metropolitan region, GRASSP was administered to one hand rather than bilaterally, engagement and satisfaction data were collected but not analysed, and no assessment of treatment fidelity, cost or usability was undertaken. Generalisability beyond this setting and this population is accordingly limited.

CONCLUSION

Immersive VR gaming was feasible, safe and well tolerated in adults with chronic incomplete tetraplegia, and over eight weeks produced greater improvement in hand function, manual dexterity, grip strength and functional independence than dose-matched conventional task-oriented training. These pilot findings provide the effect and variability estimates needed to design an adequately powered, multicentre randomised trial with an attention-matched comparator and follow-up of at least six months. Until such a trial is reported, immersive VR is best positioned as a promising adjunct to conventional upper limb rehabilitation rather than a substitute for it.

DECLARATIONS

Ethics approval and consent to participate. The study protocol was approved by the Institutional Ethics Committee of the Institute of Applied Medicines and Research, Ghaziabad, Uttar Pradesh, India (approval number [insert]; date [insert]). All participants provided written informed consent before enrolment.

Consent for publication. Not applicable; no individually identifiable data or images are included.

Availability of data and materials. The de-identified participant-level dataset generated and analysed during this study is available from the corresponding author on reasonable request.

Competing interests. The authors declare that they have no competing interests. The manufacturer of the head-mounted display had no role in the design, conduct, analysis or reporting of this study.

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Authors' contributions. MK conceived and designed the study, recruited participants, delivered the interventions, analysed the data and drafted the manuscript. MS supervised the study, contributed to design and critically revised the manuscript. RKM contributed to methodological design and critically revised the manuscript. All authors read and approved the final version.

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REFERENCES

1. Anderson KD. Targeting recovery: priorities of the spinal cord-injured population. *J Neurotrauma*. 2004;21(10):1371–83.
2. Kirshblum SC, Burns SP, Biering-Sørensen F, Donovan W, Graves DE, Jha A, et al. International standards for neurological classification of spinal cord injury (revised 2011). *J Spinal Cord Med*. 2011;34(6):535–46.
3. Coulter EH, McLean AN, Hasler JP, Allan DB, McFadyen A, Paul L. The effectiveness and satisfaction of web-based physiotherapy in people with spinal cord injury: a pilot randomised controlled trial. *Spinal Cord*. 2017;55(4):383–9.
4. Rutkowski S, Kiper P, Cacciante L, Cieřlik B, Mazurek J, Turolla A, et al. Use of virtual reality-based training in different fields of rehabilitation: a systematic review and meta-analysis. *J Rehabil Med*. 2020;52(11):jrm00121.
5. Lee HY, Kim YL, Lee SM. Effects of virtual reality-based training and task-oriented training on balance performance in stroke patients. *J Phys Ther Sci*. 2015;27(6):1883–8.
6. Souchet AD, Lourdeaux D, Burkhardt JM, Hancock PA. Design guidelines for limiting and eliminating virtual reality-induced symptoms and effects at work: a comprehensive, factor-oriented review. *Front Psychol*. 2023;14:1161932.
7. Amin F, Waris A, Syed S, Amjad I, Umar M, Iqbal J, et al. Effectiveness of immersive virtual reality-based hand rehabilitation games for improving hand motor functions in subacute stroke patients. *IEEE Trans Neural Syst Rehabil Eng*. 2024;32:2060–9.

8. Abd El-Kafy EM, Alshehri MA, El-Fiky AAR, Guermazi MA. The effect of virtual reality-based therapy on improving upper limb functions in individuals with stroke: a randomized control trial. *Front Aging Neurosci.* 2021;13:731343.
9. Rodríguez-Hernández M, Polonio-López B, Corregidor-Sánchez AI, Martín-Conty JL, Mohedano-Moriano A, Criado-Álvarez JJ. Can specific virtual reality combined with conventional rehabilitation improve poststroke hand motor function? A randomized clinical trial. *J Neuroeng Rehabil.* 2023;20(1):38.
10. Jaramillo JP, Johanson ME, Kiratli BJ. Upper limb muscle activation during sports video gaming of persons with spinal cord injury. *J Spinal Cord Med.* 2019;42(1):77–85.
11. Prasad S, Aikat R, Labani S, Khanna N. Efficacy of virtual reality in upper limb rehabilitation in patients with spinal cord injury: a pilot randomized controlled trial. *Asian Spine J.* 2018;12(5):927–34.
12. Lim DY, Hwang DM, Cho KH, Moon CW, Ahn SY. A fully immersive virtual reality method for upper limb rehabilitation in spinal cord injury. *Ann Rehabil Med.* 2020;44(4):311–9.
13. Dimbwadyo-Terrer I, Trincado-Alonso F, de los Reyes-Guzmán A, Aznar MA, Alcubilla C, Pérez-Nombela S, et al. Upper limb rehabilitation after spinal cord injury: a treatment based on a data glove and an immersive virtual reality environment. *Disabil Rehabil Assist Technol.* 2016;11(6):462–7.
14. Al Nattah MMA, Tiberti S, Segaletti L. Semi-immersive virtual reality exercise therapy for upper limb rehabilitation in patients with spinal cord injury using the Leap Motion controller. *Cureus.* 2024;16(1):e52222.
15. Gutiérrez Á, Farella N, Gil-Agudo Á, de los Reyes Guzmán A. Virtual reality environment with haptic feedback thimble for post spinal cord injury upper-limb rehabilitation. *Appl Sci.* 2021;11(6):2476.
16. De Araújo AVL, Neiva JFO, Monteiro CBM, Magalhães FH. Efficacy of virtual reality rehabilitation after spinal cord injury: a systematic review. *Biomed Res Int.* 2019;2019:7106951.
17. de Miguel-Rubio A, Rubio MD, Salazar A, Camacho R, Lucena-Anton D. Effectiveness of virtual reality on functional performance after spinal cord injury: a systematic review and meta-analysis of randomized controlled trials. *J Clin Med.* 2020;9(7):2065.
18. de Miguel-Rubio A, Rubio MD, Alba-Rueda A, Salazar A, Moral-Munoz JA, Lucena-Anton D. Virtual reality systems for upper limb motor function recovery in patients with spinal cord injury: systematic review and meta-analysis. *JMIR Mhealth Uhealth.* 2020;8(12):e22537.
19. Schulz KF, Altman DG, Moher D; CONSORT Group. CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials. *BMJ.* 2010;340:c332.
20. Eldridge SM, Chan CL, Campbell MJ, Bond CM, Hopewell S, Thabane L, et al. CONSORT 2010 statement: extension to randomised pilot and feasibility trials. *BMJ.* 2016;355:i5239.
21. Kalsi-Ryan S, Curt A, Verrier MC, Fehlings MG. Development of the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP): reviewing measurement specific to the upper limb in tetraplegia. *J Neurosurg Spine.* 2012;17(1 Suppl):65–76.
22. Kalsi-Ryan S, Beaton D, Curt A, Duff S, Popovic MR, Rudhe C, et al. The Graded Redefined Assessment of Strength Sensibility and Prehension: reliability and validity. *J Neurotrauma.* 2012;29(5):905–14.
23. Mathiowetz V, Volland G, Kashman N, Weber K. Adult norms for the Box and Block Test of manual dexterity. *Am J Occup Ther.* 1985;39(6):386–91.
24. Catz A, Itzkovich M, Agranov E, Ring H, Tamir A. SCIM — spinal cord independence measure: a new disability scale for patients with spinal cord lesions. *Spinal Cord.* 1997;35(12):850–6.
25. Catz A, Itzkovich M, Tesio L, Biering-Sorensen F, Weeks C, Laramée MT, et al. A multicenter international study on the Spinal Cord Independence Measure, version III: Rasch psychometric validation. *Spinal Cord.* 2007;45(4):275–91.