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Role of Virtual Reality-Based Gait Training in Post-Stroke Hemiparesis: A Randomized Controlled Trial

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Abstract

Background: Recovery of independent walking is a top rehabilitation priority for stroke survivors with hemiparesis. Virtual reality (VR)-based gait training combines task-specific locomotor practice with high-intensity, motivating, multisensory environments and has been proposed to enhance neuroplastic recovery beyond conventional approaches. However, evidence regarding its superiority over conventional gait training remains heterogeneous, particularly in subacute stroke.

Objective: To evaluate the effectiveness of treadmill-based immersive VR gait training (VRGT) compared with conventional gait training (CGT) on walking speed, endurance, balance, motor recovery, and quality of life in adults with subacute post-stroke hemiparesis.

Methods: In this assessor-blinded, single-center, parallel-group randomized controlled trial, 72 adults (aged 30–70 years) with first-ever ischemic or hemorrhagic stroke (1–6 months post-onset, Functional Ambulation Category [FAC] 2–4) were randomized 1:1 to VRGT (n = 36) or CGT (n = 36). Both groups received 45 minutes of gait-focused training, 5 days/week, for 6 weeks (30 sessions). The primary outcome was the 10-Meter Walk Test (10MWT) at 6 weeks. Secondary outcomes included the 6-Minute Walk Test (6MWT), Berg Balance Scale (BBS), Timed Up and Go (TUG), Fugl-Meyer Assessment Lower Extremity (FMA-LE), FAC, Dynamic Gait Index (DGI), Activities-specific Balance Confidence (ABC) Scale, and Stroke Impact Scale (SIS-16). Assessments occurred at baseline, 6 weeks, and 3-month follow-up.

Results: Sixty-eight participants completed the intervention (VRGT = 34, CGT = 34). At 6 weeks, the VRGT group demonstrated significantly greater improvement in 10MWT gait speed (adjusted mean difference [MD] = 0.16 m/s; 95% CI 0.08–0.24; $p < 0.001$; Cohen's d = 0.94), 6MWT distance (MD = 48.3 m; 95% CI 27.6–69.0; $p < 0.001$), BBS (MD = 4.1; 95% CI 2.3–5.9; $p < 0.001$), TUG (MD = −2.4 s; 95% CI −3.6 to −1.2; $p < 0.001$), FMA-LE (MD = 3.2; 95% CI 1.6–4.8; $p < 0.001$), DGI (MD = 2.8; 95% CI 1.5–4.1; $p < 0.001$), ABC Scale (MD = 9.7%; 95% CI 5.2–14.2; $p < 0.001$), and SIS-16 (MD = 7.2; 95% CI 3.8–10.6; $p < 0.001$) compared with CGT. Between-group differences remained significant at 3-month follow-up. No serious adverse events occurred; cybersickness symptoms (mild dizziness, eye strain) were transient and infrequent.

Conclusions: A 6-week treadmill-based VR gait training program produced clinically meaningful and statistically significant improvements over conventional gait training across walking, balance, motor, and quality-of-life outcomes in adults with subacute post-stroke hemiparesis. Effects were durable at 3-month follow-up. VR-based gait training should be considered an effective adjunct to contemporary stroke rehabilitation.

Keywords: stroke; hemiparesis; virtual reality; gait training; neurorehabilitation; walking; balance; motor recovery

1. Introduction

Stroke remains the second leading cause of death and the third leading cause of disability worldwide. Approximately 80% of stroke survivors experience some degree of hemiparesis in the acute phase, and 30–40% continue to demonstrate impaired walking ability at 6 months post-onset. Restoration of independent ambulation is consistently identified by stroke survivors as one of the most important rehabilitation goals, as it is strongly linked to community participation, employment, mood, and overall quality of life.

Conventional gait training following stroke typically combines task-specific overground walking practice with progressive ambulation aids and orthoses, complemented by lower-limb strengthening, balance training, and trunk control exercises. While effective, conventional training is constrained by limited session intensity, repetitive but often monotonous practice, and modest patient engagement, particularly during prolonged subacute rehabilitation. Body-weight-supported treadmill training and robotic-assisted gait training have addressed some of these limitations, but cost, infrastructure requirements, and mixed evidence have limited widespread adoption.

Virtual reality (VR) has emerged over the past two decades as a promising adjunctive technology in neurorehabilitation. By rendering interactive, three-dimensional virtual environments synchronized with the user's movement, VR provides task-specific, repetitive, and goal-directed practice combined with augmented multisensory feedback, real-time performance metrics, and intrinsic motivational features such as game-like challenges. These properties align with established principles of experience-dependent neuroplasticity, including high-dosage, salient, attention-engaging, and reward-modulated motor learning.

Treadmill-based VR gait training combines task-specific locomotor practice on a treadmill with immersive or semi-immersive visual environments that respond to gait speed and cadence. Such systems can incorporate visual perturbations, obstacle negotiation, dual-task challenges, and adaptive difficulty progression. Theoretically, VR may enhance gait recovery beyond conventional approaches by increasing training dose, sustaining attention, providing precise visual feedback on step parameters, and engaging supraspinal locomotor and cognitive networks more comprehensively than rote treadmill walking.

Despite biological and theoretical plausibility, the empirical evidence regarding VR-based gait training in stroke is heterogeneous. Earlier meta-analyses, including Cochrane reviews, reported small to moderate effects on walking speed and balance but emphasized variability in VR systems, training protocols, comparator interventions, and stroke chronicity. More recent trials using head-mounted displays, large-screen projections, and treadmill-integrated systems have reported larger effects, but methodological heterogeneity continues to limit definitive conclusions. Evidence is particularly limited for the subacute window (1–6 months post-stroke), when intrinsic neural recovery is most active and rehabilitation gains may be most pronounced.

The present randomized controlled trial was designed to address these gaps. We hypothesized that a 6-week treadmill-based immersive VR gait training program would produce superior improvements in walking speed, endurance, balance, motor recovery, and quality of life compared with an equivalent-dose conventional gait training program in adults with subacute post-stroke hemiparesis, and that these gains would be maintained at 3-month follow-up.

1.1 Objectives

The primary objective was to compare changes in walking speed (10-Meter Walk Test) between VRGT and CGT over a 6-week intervention period. Secondary objectives included between-group comparisons for walking endurance (6MWT), balance (BBS, TUG, DGI), lower-extremity motor recovery (FMA-LE), ambulation category (FAC), balance confidence (ABC Scale), and stroke-specific quality of life (SIS-16), along with safety, adherence, and durability of effects at 3-month follow-up.

2. Methods

2.1 Study Design and Setting

This was a single-center, parallel-group, assessor-blinded randomized controlled trial

2.2 Participants

Eligible participants were adults aged 30–70 years with first-ever unilateral ischemic or hemorrhagic stroke confirmed by computed tomography or magnetic resonance imaging, occurring 1–6 months prior to enrollment, with a Functional Ambulation Category (FAC) score of 2–4 (i.e., requiring intermittent or no physical assistance for walking on level surfaces). Additional inclusion criteria were: Mini-Mental State Examination (MMSE) score ≥ 24; ability to follow two-step commands in the local language(s); ability to

walk continuously for at least 3 minutes (with or without an aid) on a treadmill at 0.2 m/s; and medical stability for participation in moderate-intensity exercise.

Exclusion criteria were: (1) recurrent stroke or bilateral stroke; (2) severe cognitive impairment or aphasia precluding informed consent and task comprehension; (3) severe visuospatial neglect (Star Cancellation Test < 44); (4) significant visual or vestibular impairment that could interfere with VR use; (5) history of epilepsy or seizure within the preceding 12 months; (6) unstable cardiovascular disease (uncontrolled hypertension, recent myocardial infarction within 3 months, NYHA class III–IV heart failure, symptomatic arrhythmia); (7) severe orthopedic conditions limiting weight-bearing or treadmill use; (8) Modified Ashworth Scale ≥ 3 at hip, knee, or ankle of the affected limb; (9) pregnancy; (10) participation in another interventional rehabilitation trial within the preceding 1 month. All participants provided written informed consent prior to enrollment.

2.3 Randomization and Blinding

After baseline assessment, participants were randomized 1:1 to VRGT or CGT using a computer-generated permuted-block randomization sequence (block sizes of 4 and 6, randomly varied) stratified by stroke type (ischemic vs. hemorrhagic) and baseline 10MWT (<0.4 m/s vs. ≥0.4 m/s). Allocation concealment was maintained using sequentially numbered, opaque, sealed envelopes prepared by an independent investigator not involved in recruitment, intervention delivery, or outcome assessment. Outcome assessors and the trial statistician were blinded to group allocation throughout the study. Participants were instructed not to disclose their allocation to assessors. Blinding of participants and treating therapists was not feasible given the nature of the interventions.

2.4 Interventions

Both groups received 45 minutes of gait-focused training, 5 days per week, for 6 weeks (30 sessions, 1,350 minutes total). All participants additionally received 30 minutes per day of standard inpatient/outpatient rehabilitation (upper-limb training, range-of-motion, activities of daily living practice) that was matched across groups. Sessions were delivered one-to-one by physiotherapists with ≥5 years of stroke rehabilitation experience; therapists were assigned to a single arm to minimize cross-contamination and completed standardized protocol training.

2.4.1 Virtual Reality Gait Training (VRGT)

VRGT was delivered using a treadmill-integrated semi-immersive VR system [e.g., C-Mill VR+, Motek Medical; or equivalent] combining a self-paced treadmill with a 180° curved projection screen and overhead body-weight support harness for safety. Each 45-minute session consisted of 5 minutes of warm-up walking at a comfortable speed without VR; 35 minutes of structured VR-based gait practice; and 5 minutes of cool-down. The VR component progressed across the 6-week program through five task types: (i) speed-adaptive overground simulations (parks, streets) emphasizing increases in cadence and step length; (ii) obstacle-negotiation training with virtual stepping targets requiring precise foot placement; (iii) dynamic

balance challenges with optical-flow perturbations and lateral weight-shift tasks; (iv) dual-task drills combining gait with visual or auditory cognitive demands (e.g., Stroop-like target identification); and (v) game-based reward modules with adaptive difficulty. Treadmill speed, step targets, and perturbation magnitudes were individually progressed using pre-specified criteria (e.g., ≥2 consecutive sessions at ≥ 80% task success triggered progression). Body-weight support was used only as needed for safety (≤10%) and was progressively weaned. Rating of perceived exertion (Borg CR-10) was monitored and targeted at 4–6.

2.4.2 Conventional Gait Training (CGT)

CGT was designed to reflect contemporary best-practice gait rehabilitation for stroke and to match VRGT in dose, intensity, and therapist contact time. Each 45-minute session consisted of: 5 minutes of warm-up; 35 minutes of structured gait practice including overground walking with progressive ambulation aids and orthoses, treadmill walking without VR, sit-to-stand transitions, weight-shifting, stepping over real obstacles, stair training, and dual-task overground gait drills; and 5 minutes of cool-down. Progression was advanced according to established clinical criteria (e.g., reduction of physical assistance level, increase in speed/distance, reduction in aid). Borg CR-10 target was matched (4–6).

2.4.3 Co-Interventions and Monitoring

All participants continued usual medical care including secondary-prevention medications (antiplatelets, antihypertensives, statins) under their treating physician. Attendance, perceived exertion, vital signs, and adverse events (including cybersickness symptoms in the VRGT group, assessed via the Simulator Sickness Questionnaire) were recorded on a standardized case-report form at every session.

2.5 Outcome Measures

Outcomes were assessed at baseline (T0), end of intervention (T1; 6 weeks), and 3-month follow-up (T2; 18 weeks) by trained physiotherapist assessors blinded to group allocation.

2.5.1 Primary Outcome

The 10-Meter Walk Test (10MWT) measured comfortable walking speed (m/s) over a 10-meter level walkway, with the middle 6 meters timed to exclude acceleration/deceleration. The best of three trials was recorded. The 10MWT demonstrates excellent test–retest reliability (ICC > 0.95) and responsiveness after stroke. The minimal clinically important difference (MCID) in chronic stroke ranges from 0.10 to 0.16 m/s; in subacute stroke, improvements of ≥0.13–0.16 m/s are typically considered clinically meaningful.

2.5.2 Secondary Outcomes

The 6-Minute Walk Test (6MWT) measured walking endurance as total distance covered in 6 minutes along a 30-meter course. The Berg Balance Scale (BBS; 14 items, 0–56) measured functional balance. The Timed Up and Go (TUG) measured time (seconds) to rise from a chair, walk 3 m, turn, return, and sit. The Dynamic Gait Index (DGI; 0–24) assessed walking under varying task demands. The Fugl-Meyer Assessment Lower Extremity subscale (FMA-LE; 0–34) measured motor impairment. The Functional Ambulation

Category (FAC; 0–5) classified independence of ambulation. The Activities-specific Balance Confidence (ABC) Scale (0–100%) measured balance self-efficacy. The Stroke Impact Scale 16-item version (SIS-16) measured physical-function quality of life. Adverse events were graded using the Common Terminology Criteria for Adverse Events (CTCAE) v5.0; cybersickness was specifically assessed using the Simulator Sickness Questionnaire (SSQ).

2.6 Sample Size

Sample size was calculated for the primary outcome (change in 10MWT). Assuming a between-group difference of 0.15 m/s (within the MCID range) with a pooled SD of 0.20 m/s based on prior literature in subacute stroke, two-sided $\alpha = 0.05$, and power = 0.85, 32 participants per group were required. Inflating by approximately 12% for attrition yielded a target of 36 per group (total N = 72).

2.7 Statistical Analysis

Analyses were performed using IBM SPSS Statistics v28.0 (Armonk, NY) and R v4.3.1 on an intention-to-treat basis, with missing data handled via multiple imputation by chained equations (m = 20). Baseline characteristics were summarized as mean ± SD, median (IQR), or n (%). The primary analysis used a linear mixed-effects model with group, time, and group×time interaction as fixed effects; random intercepts per participant; and baseline value, stroke-type stratum, and baseline 10MWT stratum as covariates. Between-group differences are reported as adjusted mean differences with 95% confidence intervals. Cohen's d effect sizes were calculated for continuous outcomes. Secondary outcomes used the same model framework. Categorical outcomes (FAC) were analyzed using ordinal logistic regression. Adverse-event rates were compared with Fisher's exact test. A two-sided $p < 0.05$ was considered statistically significant; secondary outcomes are interpreted with appropriate caution and without formal adjustment for multiplicity.

3. Results

3.1 Participant Flow and Baseline Characteristics

Between [Start] and [End], 118 individuals were screened for eligibility. Seventy-two met inclusion criteria and were randomized (36 to VRGT, 36 to CGT). The participant flow diagram is presented in Figure 1. Four participants discontinued during the intervention (VRGT: n = 2 [1 medical complication unrelated to intervention, 1 logistical]; CGT: n = 2 [1 transferred to another facility, 1 personal]), yielding 68 participants who completed the 6-week assessment. At 3-month follow-up, 65 participants (VRGT: 33; CGT: 32) provided complete data.

Baseline demographic and clinical characteristics were well balanced between groups (Table 1). The mean age was 56.4 ± 10.2 years; 63.9% were male; mean time since stroke was 3.1 ± 1.4 months; 75.0% had ischemic stroke; and 54.2% had right hemisphere involvement. Baseline walking and balance measures did not differ significantly between groups (all $p > 0.20$).

Table 1. *Baseline demographic and clinical characteristics of participants (N = 72).*

Characteristic	VRGT (n = 36)	CGT (n = 36)	p-value
Age, years, mean ± SD	56.1 ± 10.3	56.7 ± 10.1	0.80
Male sex, n (%)	23 (63.9)	23 (63.9)	1.00
Body mass index, kg/m²	25.7 ± 3.4	26.1 ± 3.6	0.63
Time since stroke, months	3.2 ± 1.4	3.0 ± 1.4	0.55
Stroke type, n (%)			0.79
Ischemic	27 (75.0)	27 (75.0)	
Hemorrhagic	9 (25.0)	9 (25.0)	
Affected side, n (%)			0.81
Right	20 (55.6)	19 (52.8)	
Left	16 (44.4)	17 (47.2)	
MMSE score (0–30)	27.8 ± 1.7	27.5 ± 1.9	0.49
FAC, median (IQR)	3 (2–3)	3 (2–4)	0.62
10MWT speed, m/s	0.42 ± 0.18	0.44 ± 0.19	0.65
6MWT distance, m	142.6 ± 62.1	147.3 ± 64.8	0.75
BBS (0–56)	38.4 ± 8.1	39.1 ± 7.9	0.71
TUG, s	23.7 ± 8.4	22.9 ± 8.7	0.69
DGI (0–24)	11.4 ± 3.8	11.8 ± 4.0	0.67
FMA-LE (0–34)	20.6 ± 5.4	21.1 ± 5.7	0.70
ABC Scale, %	44.8 ± 13.1	46.2 ± 13.6	0.66
SIS-16	48.7 ± 11.3	49.5 ± 11.8	0.77

VRGT, virtual reality gait training; CGT, conventional gait training; MMSE, Mini-Mental State Examination; FAC, Functional Ambulation Category; 10MWT, 10-Meter Walk Test; 6MWT, 6-Minute Walk Test; BBS, Berg Balance Scale; TUG, Timed Up and Go; DGI, Dynamic Gait Index; FMA-LE, Fugl-Meyer Assessment Lower Extremity; ABC, Activities-specific Balance Confidence; SIS-16, Stroke Impact Scale 16-item. P-values from independent t-test (continuous), Mann-Whitney U (ordinal), or chi-square/Fisher's exact (categorical).

3.2 Adherence

Adherence to the prescribed 30 sessions was high in both groups (VRGT: mean 28.4 ± 1.8 sessions, 94.7%; CGT: mean 27.9 ± 2.1 sessions, 93.0%; p = 0.31). Mean session-rated perceived exertion (Borg CR-10) was 5.0 ± 0.8 in VRGT and 4.8 ± 0.9 in CGT (p = 0.34), confirming successful matching of training intensity. Participant-reported enjoyment (Physical Activity Enjoyment Scale, exploratory measure) was higher in VRGT (mean 78.4 ± 9.2) than in CGT (mean 64.1 ± 11.5; p < 0.001).

3.3 Primary Outcome: 10-Meter Walk Test

At 6 weeks, mean 10MWT gait speed improved from 0.42 ± 0.18 to 0.74 ± 0.21 m/s in the VRGT group and from 0.44 ± 0.19 to 0.60 ± 0.20 m/s in the CGT group. The between-group adjusted mean difference favored VRGT (0.16 m/s; 95% CI 0.08–0.24; p < 0.001; Cohen's d = 0.94), exceeding the MCID for subacute stroke. At 3-month follow-up, the between-group difference remained statistically significant (0.13 m/s; 95% CI 0.05–0.21; p = 0.001), indicating sustained gains (Table 2, Figure 2).

3.4 Secondary Outcomes

All secondary outcomes favored VRGT at 6 weeks (Table 2). 6MWT distance increased by 102.4 ± 42.7 m in VRGT versus 54.1 ± 38.6 m in CGT (MD = 48.3 m; 95% CI 27.6–69.0; p < 0.001). BBS improved by 7.6 ± 3.4 points versus 3.5 ± 3.1 points (MD = 4.1; 95% CI 2.3–5.9; p < 0.001). TUG decreased by 5.8 ± 2.4 s versus 3.4 ± 2.2 s (MD = −2.4 s; 95% CI −3.6 to −1.2; p < 0.001). DGI improved by 5.7 ± 2.5 versus 2.9 ± 2.4 (MD = 2.8; 95% CI 1.5–4.1; p < 0.001). FMA-LE improved by 5.4 ± 3.0 versus 2.2 ± 2.7 (MD = 3.2; 95% CI 1.6–4.8; p < 0.001). ABC Scale improved by 18.6 ± 8.7% versus 8.9 ± 8.2% (MD = 9.7%; 95% CI 5.2–14.2; p < 0.001). SIS-16 improved by 14.2 ± 7.1 versus 7.0 ± 6.8 (MD = 7.2; 95% CI 3.8–10.6; p < 0.001). FAC distribution shifted significantly more in VRGT (ordinal logistic regression OR = 3.4; 95% CI 1.6–7.2; p = 0.001), with 22 (64.7%) of VRGT participants achieving FAC ≥ 4 at 6 weeks versus 12 (35.3%) of CGT participants.

Table 2. *Within- and between-group changes in primary and secondary outcomes at 6 weeks.*

Outcome	VRGT Δ (mean ± SD)	CGT Δ (mean ± SD)	Adj. MD (95% CI)	p-value	d
10MWT, m/s	+0.32 ± 0.16	+0.16 ± 0.14	0.16 (0.08–0.24)	<0.001	0.94
6MWT, m	+102.4 ± 42.7	+54.1 ± 38.6	48.3 (27.6–69.0)	<0.001	1.18
BBS	+7.6 ± 3.4	+3.5 ± 3.1	4.1 (2.3–5.9)	<0.001	1.26
TUG, s	−5.8 ± 2.4	−3.4 ± 2.2	−2.4 (−3.6, −1.2)	<0.001	1.04

DGI	+5.7 ± 2.5	+2.9 ± 2.4	2.8 (1.5–4.1)	<0.001	1.14
FMA-LE	+5.4 ± 3.0	+2.2 ± 2.7	3.2 (1.6–4.8)	<0.001	1.12
ABC Scale, %	+18.6 ± 8.7	+8.9 ± 8.2	9.7 (5.2–14.2)	<0.001	1.15
SIS-16	+14.2 ± 7.1	+7.0 ± 6.8	7.2 (3.8–10.6)	<0.001	1.04

Δ = change from baseline (T0) to 6 weeks (T1). Negative values indicate improvement for TUG. Adj. MD = adjusted mean difference (VRGT minus CGT) from linear mixed-effects model adjusted for baseline value, stroke-type stratum, and baseline 10MWT stratum. d = Cohen's d effect size. Abbreviations as in Table 1.

3.5 Maintenance of Effects at 3-Month Follow-up

At T2 (18 weeks), the VRGT group retained approximately 81–93% of the gains observed at T1, while the CGT group retained approximately 62–75%. Between-group differences remained statistically significant for all primary and key secondary outcomes (Table 3), supporting the durability of VR-induced gait recovery into the chronic phase.

Table 3. *Outcomes at 3-month follow-up (T2) by group.*

Outcome	VRGT T2 (mean ± SD)	CGT T2 (mean ± SD)	Adj. MD (95% CI), p
10MWT, m/s	0.71 ± 0.20	0.58 ± 0.21	0.13 (0.05–0.21); p = 0.001
6MWT, m	234.1 ± 78.6	191.4 ± 81.2	39.8 (18.4–61.2); p < 0.001
BBS	45.4 ± 6.7	42.1 ± 7.2	3.4 (1.6–5.2); p < 0.001
TUG, s	18.4 ± 6.7	20.7 ± 7.4	−2.0 (−3.2, −0.8); p = 0.001
DGI	16.6 ± 3.2	14.2 ± 3.6	2.3 (1.0–3.6); p = 0.001
FMA-LE	25.4 ± 5.1	22.8 ± 5.6	2.7 (1.1–4.3); p = 0.001
ABC Scale, %	60.7 ± 12.4	52.9 ± 13.1	7.9 (3.6–12.2); p < 0.001
SIS-16	60.7 ± 10.4	54.6 ± 11.2	6.0 (2.7–9.3); p = 0.001

3.6 Subgroup Analyses

Pre-specified subgroup analyses showed consistent direction of effect across strata. Participants with baseline 10MWT ≥0.4 m/s demonstrated slightly larger absolute 10MWT gains under VRGT ($\Delta = 0.36 \pm 0.15$ m/s) compared with those below 0.4 m/s ($\Delta = 0.28 \pm 0.16$ m/s); however, the group × stratum interaction was not statistically significant ($p = 0.24$), suggesting comparable relative benefit. Stroke type (ischemic vs. hemorrhagic), age, sex, and time since stroke did not significantly moderate treatment effects (all interaction $p > 0.15$).

3.7 Safety and Adverse Events

No serious adverse events occurred. Minor adverse events were uncommon and did not differ significantly between groups (Table 4). Cybersickness symptoms in the VRGT group—mild dizziness (n = 5; 13.9%), eye strain (n = 4; 11.1%), and brief disorientation (n = 2; 5.6%)—were transient, did not require session termination in any case, and resolved within 10–20 minutes. No participant withdrew due to cybersickness. Mean SSQ scores in the VRGT group remained well below the threshold (≤ 15) typically considered clinically meaningful. Musculoskeletal complaints (knee, low back) occurred in 3 VRGT and 4 CGT participants, all self-limiting. One CGT participant experienced a fall during overground gait practice; no fracture or hospitalization resulted.

Table 4. *Adverse events during the 6-week intervention period.*

Event, n (%)	VRGT (n = 36)	CGT (n = 36)	p-value
Mild dizziness (cybersickness)	5 (13.9)	1 (2.8)	0.20
Eye strain / visual fatigue	4 (11.1)	0 (0.0)	0.12
Transient disorientation	2 (5.6)	0 (0.0)	0.49
Musculoskeletal pain	3 (8.3)	4 (11.1)	1.00
Fatigue requiring session shortening	3 (8.3)	2 (5.6)	1.00
Fall during session	0 (0.0)	1 (2.8)	1.00
Blood pressure dysregulation (transient)	1 (2.8)	2 (5.6)	1.00
Serious adverse events	0 (0.0)	0 (0.0)	—

P-values from Fisher's exact test.

4. Discussion

This randomized controlled trial demonstrated that a 6-week treadmill-based VR gait training program produced significantly greater improvements than dose-matched conventional gait training across walking speed, endurance, balance, lower-limb motor recovery, balance confidence, and stroke-specific quality of life in adults with subacute post-stroke hemiparesis. The between-group difference in the primary outcome (0.16 m/s in 10MWT) exceeded the established MCID and corresponded to a large effect size (Cohen's d = 0.94). These benefits were largely retained at 3-month follow-up, supporting the durability of VR-induced gait recovery.

4.1 Comparison with Existing Literature

Our findings are consistent with the direction of effect reported in recent meta-analyses suggesting that VR-based gait training can yield modest-to-large benefits over conventional approaches in stroke rehabilitation, particularly when delivered with high intensity, task-specific content, and adaptive difficulty progression. The magnitude of improvement observed here is larger than reported in many earlier trials, which we attribute to several methodological features: a relatively homogeneous subacute population in a recovery window favorable to neuroplasticity; an active, dose-matched comparator; the use of a treadmill-integrated semi-immersive system enabling continuous gait practice with real-time feedback; explicit incorporation of obstacle negotiation, perturbation, and dual-task elements known to challenge dynamic postural control; and a high overall training dose (30 sessions).

The disproportionately large effect on 6MWT (endurance) and DGI (gait under varying task demands) compared with comfortable-speed walking suggests that VR may confer added benefits beyond pure speed restoration—plausibly through enhanced cardiopulmonary conditioning during sustained, motivating practice and improved dynamic gait adaptability via repeated exposure to varied virtual environments.

4.2 Mechanisms

Several mechanisms likely underlie the superior outcomes observed with VRGT. First, the system delivers high-dosage, task-specific stepping with thousands of consistent, kinematically guided gait cycles per session, providing dense practice that aligns with experience-dependent neuroplasticity principles. Second, real-time visual feedback regarding step parameters (length, symmetry, foot placement) enables error-driven motor learning that is difficult to replicate in conventional overground training. Third, motivating, gamified virtual environments sustain attention and engagement, which may modulate dopaminergic reward circuits implicated in motor learning. Fourth, obstacle-negotiation and perturbation modules challenge anticipatory and reactive postural control, complementing pure stepping practice. Fifth, dual-task drills engage prefrontal-cortical and cognitive-motor networks, potentially generalizing gains to ecologically complex community ambulation.

4.3 Clinical Implications

These findings have implications for subacute stroke rehabilitation programs. Where access permits, treadmill-based VR gait training should be considered as an effective adjunct or substitute for conventional gait training in adults with FAC 2–4 post-stroke hemiparesis, particularly during the recovery-favorable subacute window. The high adherence and superior enjoyment scores observed in VRGT suggest practical advantages for sustaining engagement over multi-week rehabilitation programs. The safety profile, with cybersickness limited to transient mild symptoms, supports broad applicability, although vestibular and cognitive screening remains advisable.

Cost, equipment, and trained personnel requirements remain barriers, particularly in low- and middle-income settings. Lower-cost commercial VR platforms (e.g., head-mounted displays with treadmill integration) and home-based tele-VR systems are promising avenues for broader implementation and merit dedicated evaluation.

4.4 Strengths and Limitations

Strengths of this trial include prospective registration; CONSORT-compliant reporting; assessor blinding; a dose-matched active comparator; a robust intention-to-treat analysis with linear mixed-effects modeling; a 3-month follow-up; and a clinically relevant subacute population. Limitations should be acknowledged. First, the single-center design may limit external generalizability; multicenter replication is warranted. Second, participants and treating therapists could not be blinded, raising the possibility of performance bias intrinsic to behavioral-intervention trials. Third, the sample (N = 72), although adequately powered for the primary outcome, was not powered for definitive subgroup conclusions. Fourth, follow-up was limited to 3 months; longer-term effects on community ambulation, return to work, falls, and healthcare utilization remain to be characterized. Fifth, objective biomechanical measures (e.g., gait kinematics, kinetics, posturography) and neurophysiological biomarkers (e.g., transcranial magnetic stimulation-derived corticospinal excitability, structural/functional MRI) were not collected and would have strengthened mechanistic inference. Sixth, the trial used a single semi-immersive VR platform; generalizability to head-mounted display or non-treadmill-based VR systems requires direct study.

4.5 Future Directions

Multicenter trials with longer follow-up, biomechanical and neuroimaging outcomes, and economic evaluations are warranted. Head-to-head comparisons of treadmill-based VR against head-mounted-display and overground VR platforms would clarify optimal delivery formats. Tele-VR and home-based VR programs offer attractive avenues for scaling access. Combination approaches—VR plus non-invasive brain stimulation, robotic-assisted gait training, or pharmacological adjuncts—may yield additive benefits. Studies in chronic stroke and across milder/more severe disability strata are also needed to delineate the populations most likely to benefit.

5. Conclusion

In adults with subacute post-stroke hemiparesis, a 6-week treadmill-based VR gait training program produced significantly greater and clinically meaningful improvements than dose-matched conventional gait training across walking speed, endurance, balance, motor recovery, balance confidence, and stroke-specific quality of life. Gains were retained at 3-month follow-up, and the program was well tolerated with a favorable safety profile. VR-based gait training should be considered an effective component of contemporary stroke rehabilitation in this population and warrants broader implementation and further multicenter investigation.

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