

A Pilot Study Evaluating Virtual Reality-Based Real-Time Feedback for Gait Training in Individuals with Chronic Stroke

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Abstract

Virtual reality (VR) training has gained widespread use in stroke rehabilitation because it can foster brain plasticity and support functional recovery. This study evaluated the impact of treadmill-based gait training incorporating VR with real-time feedback on motor function, balance, and spatiotemporal gait variables among individuals with chronic stroke. Fifteen chronic stroke patients ($n = 15$) were randomly allocated to either an experimental group ($n = 8$) receiving treadmill gait training with VR-based real-time feedback or a control group ($n = 7$) undergoing standard treadmill gait training. The experimental group utilized a treadmill, Oculus Rift VR headset, and smart insoles during sessions. Participants in this group engaged in 30-minute training sessions three times per week for 5 weeks while wearing the VR device. The control group performed treadmill walking for an equivalent duration without VR. Motor function was assessed with the Fugl-Meyer Assessment. Balance was evaluated using the Timed Up and Go test and Berg Balance Scale. Gait parameters were measured via the Optogait system. Data normality was checked with the Shapiro-Wilk test; within-group changes were analyzed using the Wilcoxon signed-rank test, and between-group differences with the Mann-Whitney U test. Both groups demonstrated significant gains in motor function, balance, and gait performance. However, the experimental group exhibited markedly greater improvements compared to the control group in Fugl-Meyer scores (4.75 vs. 1.57, $P < 0.05$), Timed Up and Go test (-3.10 vs. -1.12 s), Berg Balance Scale (3.00 vs. 1.71), affected step length (5.35 vs. 2.01 cm), stride length (3.86 vs. 1.75 cm), affected single support time (2.61% vs. 1.22%), and cadence (0.07 vs. 0.02 steps/min) (all $P < 0.05$). Findings indicate that integrating real-time VR feedback during treadmill gait training yields superior benefits for motor function, balance, and gait performance in post-stroke patients.

Keywords: Virtual reality, Real-time feedback, Balance, Gait

Introduction

Stroke survivors often face diverse disabilities that vary according to the location and extent of brain damage, profoundly affecting their everyday functioning [1]. These impairments commonly encompass motor deficits, sensory loss, and cognitive challenges [2]. Such issues

frequently compromise postural stability, leading to difficulties with balance and ambulation [3].

Extensive research has explored interventions to mitigate functional limitations in stroke patients. Proven therapeutic approaches include Proprioceptive Neuromuscular Facilitation (PNF), Bobath therapy, Rood therapy, Constraint-Induced Movement Therapy (CIMT), task-oriented training, and virtual reality techniques [4-7]. These methods help patients transition from atypical movement patterns toward more normal ones, with their efficacy in improving functional outcomes well documented across multiple investigations [8].

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Balance plays a critical role in achieving independence [9]. Post-stroke balance problems stem from multiple sources, such as impaired sensation and vestibular dysfunction [10]. Affected individuals often have trouble controlling their center of mass and performing goal-directed tasks, which heightens fall risk [11].

Gait represents a cornerstone of functional autonomy, enabling mobility within various settings [12]. Approximately 22% of stroke patients with gait impairments never recover independent walking ability [13]. Typical post-stroke gait abnormalities include slowed walking speed [14], circumduction [15], and hyperextended knees [16]. Treadmill training has been employed in diverse formats to address walking deficits, yet conventional treadmill exercises can feel monotonous and fail to sustain patient motivation [17].

In recent years, there has been growing emphasis on technology-assisted rehabilitation, particularly virtual reality (VR), for stroke recovery. VR interventions have shown promise in enhancing upper extremity function, balance, gait, general motor abilities, and cognition [18]. A key benefit over conventional therapies is VR's immersive, game-like nature, which boosts patient engagement, attention, motivation, and compliance [19]. VR combined with remote monitoring has also expanded, enabling home-based treatment with direct professional oversight and immediate feedback [20]. Studies confirm that VR training is a safe, cost-effective option for improving lower-limb strength, balance, stair negotiation, ankle mobility, range of motion, and gait speed in stroke survivors [21, 22].

Virtual reality creates simulated environments that closely replicate real-world experiences through specialized hardware [23]. VR systems are generally divided into non-immersive and fully immersive categories depending on the degree of sensory engagement [24]. Non-immersive VR, the most prevalent form, involves interaction via everyday devices such as smartphones, computers, or TVs using standard input tools like mice or keyboards [25]. Fully immersive VR employs head-mounted displays to block external sensory input and deliver highly realistic computer-generated scenarios [26].

VR-based training promotes neuroplasticity and facilitates the reacquisition of motor skills and patterns [27]. Prior work has reported improvements in outcomes such as the 10-meter walk test and the Timed Up and Go test [28], as well as stride duration and cadence [29]. Additional studies have examined VR combined with

treadmill training [4], robotics [30], and electromyography (EMG) biofeedback [31]. Nevertheless, most existing literature focuses on general VR applications, with limited evidence specifically addressing balance and gait training that incorporates real-time feedback. In particular, comprehensive data on effects across motor function, balance, and gait remain scarce [31].

Consequently, the current study examined how a VR gait-training program with real-time feedback influences motor function, balance, and spatiotemporal gait characteristics in individuals with chronic stroke.

Materials and Methods

Research design

This investigation employed a single-blind, randomized pretest-posttest controlled pilot study design. A licensed physical therapist possessing more than five years of clinical practice and a master's degree performed all assessments and interventions while remaining blinded to participant group allocation. Participants were instructed to halt the session and rest immediately if they experienced dizziness or any other discomfort.

The study protocol was registered in the Clinical Research Information Service database, and the university's Institutional Review Board (GU-202207-HRa-05-01-P) granted ethical approval. Data collection occurred over five weeks, spanning from 1 May 2023 to 2 June 2023, following IRB clearance. All individuals provided written informed consent after reviewing the study information and agreed to participate voluntarily. Although industry-sponsored, the research team independently handled study design, data analysis, manuscript preparation, revisions, and submission without external influence from the sponsor.

Subjects

15 individuals with stroke receiving outpatient services at Hospital B in Seongnam, Gyeonggi Province, participated in this study.

Participants were recruited through informational posters displayed in the physical therapy department. Interested candidates received detailed study explanations and signed consent forms before enrollment. Selection prioritized patients whose gait limitations (such as shortened stride length and balance deficits) aligned with the VR system's capabilities. Given constraints in applying VR to individuals with profound mobility

restrictions, we included only those with a Modified Ashworth Scale (MAS) score of 2 or lower and the ability to walk independently to a minimal degree. Out of 18 initial volunteers, 15 were ultimately deemed suitable after screening. Inclusion and exclusion criteria are detailed below.

Inclusion criteria

Stroke onset at least six months prior with the capacity for at least minimal independent ambulation.

Functional Ambulation Classification (FAC) score of 3 or lower.

Score of 21 or above on the Korean Mini-Mental State Examination, demonstrating sufficient cognitive and communicative ability.

No history of allergic reaction to functional electrical stimulation.

Absence of ankle joint contractures that would interfere with walking.

Exclusion criteria

Individuals presenting with vestibular or cerebellar dysfunction, significant visual or hearing deficits, prior orthopedic surgery on the lower limbs, cardiovascular complications, or additional neurological conditions impacting the lower extremities were not eligible for participation.

Procedure

Before and after the five-week intervention period, all study participants underwent evaluations of motor function, balance, and gait performance. Before beginning the trial, subjects received a thorough briefing on the study protocols. Using a computer-generated randomization table, participants were allocated to the experimental or control group in a 1:1 ratio. Each participant completed 30-minute intervention sessions five days per week, for a total of 15 sessions. In addition, both groups engaged in a conventional rehabilitation program consisting of 30-minute sessions once daily, five days a week.

Research methods

Experimental group

Participants in the experimental group engaged in treadmill gait training while equipped with an Oculus Rift headset and smart insoles (SPINA Systems Co., Ltd., R-C-SPO-Pedisol250, Republic of Korea). They performed VR-enhanced gait training on a treadmill (HP

Cosmos, QUASAR MED, Germany) with the Oculus Rift and received real-time visual feedback from the smart insoles. Before walking, sensors were calibrated by pressing the calibration button while standing to verify proper function.

During training, individuals received immediate visual feedback regarding center of pressure (COP) displacement and weight distribution between the affected and unaffected limbs. This information appeared as bar graphs on both sides, illustrating weight-shifting and loading patterns to guide participants toward balanced weight-bearing on both sides.

Before the main sessions, participants received detailed instructions and a 10-minute familiarization period to ensure comfortable adaptation to the VR real-time feedback system. Treadmill speed was adjusted to each participant's preferred comfortable pace. The VR environment featured a pre-recorded 3D outdoor walking scenario uploaded to an online platform for use with the headset.

Each VR session comprised 5 minutes of park walking, 5 minutes of city walking, and 5 minutes of simulated shopping. A 5-minute rest period followed each 5-minute VR segment to minimize muscle fatigue and dizziness before continuing [32]. The real-time feedback VR training lasted 15 minutes in total per session, supplemented by 30 minutes of standard physical therapy.

A physical therapist with more than 10 years of experience and neurodevelopmental treatment certification oversaw and delivered the VR intervention. The VR real-time feedback training lasted 30 minutes per day, three times weekly over five weeks (15 sessions total). Conventional physical therapy was delivered for 30 minutes daily, five days a week. The same therapist—who held a master's degree and three years of clinical experience—administered both the VR training and traditional therapy. Conventional sessions incorporated Bobath techniques, Proprioceptive Neuromuscular Facilitation (PNF), range-of-motion exercises, strengthening, stretching, overground walking, and cycling activities.

Control group

The control group completed treadmill gait training under identical conditions to the experimental group, except without VR components. Sessions consisted of 5 minutes of walking followed by 5 minutes of rest, repeated for 3 sets. Participants also received 30 minutes

of conventional physical therapy in conjunction with the 30-minute treadmill training.

Measurement items

Motor function

Lower extremity motor function was assessed using the Fugl-Meyer Assessment (FMA), which includes 17 items scored from 0 to 34 points. Items evaluate reflex activity, hip/knee/ankle coordination, and voluntary movements. This tool demonstrates strong inter-rater reliability ($r \geq 0.96$) and concurrent validity ($r \geq 0.99$) in stroke populations, establishing it as a dependable instrument [33].

Balance ability

Balance was measured with the Berg Balance Scale, which assesses performance across sitting, standing, and positional changes through 14 items. Each item is scored 0–4, yielding a maximum of 56 points; higher scores reflect superior balance. Intra-rater reliability is $r = 0.99$ and inter-rater reliability is $r = 0.97$ [34, 35]. The Timed Up and Go (TUG) test further evaluated dynamic balance. Participants began seated in a chair with armrests, stood upon command, walked 3 meters, turned, and returned to sit. They were instructed to turn toward the unaffected side. The test was performed three times, with the average recorded. Intra-rater reliability reached $r = 0.99$ and inter-rater reliability $r = 0.98$ [36].

Gait ability

Spatiotemporal gait parameters were quantified using the OptoGait system (Microgate S.r.l, Italy), consisting of two 4-meter transmitting/receiving bars and a Logitech Pro 9000 webcam. Bars were positioned 1 meter apart on the floor, with LEDs spaced at 1 cm intervals transmitting continuous infrared signals. Participants walked 10 meters at a self-selected comfortable speed on a level surface; data from the middle 6 meters (excluding the first and last 2 meters) were analyzed. Key variables

included weight-bearing on the affected side, single-support time, double-support time, step length, and velocity. One experienced physical therapist performed all assessments to minimize variability. The system shows excellent intra-rater reliability ($r = 0.99$) and test-retest reliability ($r = 0.98$ – 0.99) [37].

Data analysis

The sample size was determined based on prior research findings. Using G*Power software (version 3.1.9.4), calculations with 80% power, $\alpha = 0.05$, and an effect size of 0.723 yielded a required total of 15 participants.

Statistical analyses were performed using SPSS version 21.0. Normality was evaluated via the Shapiro–Wilk test. Baseline homogeneity of general characteristics between groups was examined using independent-samples t-tests for continuous variables and chi-square tests for categorical variables. Within-group pre- to post-intervention changes were analyzed with the Wilcoxon signed-rank test. Between-group differences in the magnitude of change were compared using the Mann–Whitney U test. Statistical significance was established at $\alpha \leq 0.05$.

Results and Discussion

General characteristics of the subjects

Table 1 summarizes participant demographics. The experimental group averaged 52.75 ± 10.70 years, compared with 51.71 ± 7.67 years in the control group, with no significant difference ($P > 0.05$). Mean height was 166.40 ± 3.76 cm in the experimental group and 166.94 ± 7.94 cm in the control group ($P > 0.05$). Average body weight was 67.63 ± 6.41 kg for the experimental group and 72.18 ± 9.26 kg for the control group ($P > 0.05$). The gender distribution was 3 males and 5 females in the experimental group versus 4 males and 3 females in the control group, with no significant between-group difference ($P > 0.05$).

Table 1. General characteristics of subjects (n = 15).

	Experimental group (n = 8)	Control group (n = 7)	t/x ² (P)
Age (years)	52.75 ± 10.70 ^a	51.71 ± 7.67	−0.212 ^b (0.835 ^c)
Weight (kg)	67.63 ± 6.41	72.18 ± 9.26	−1.118 (0.284)
Height (cm)	166.40 ± 3.76	166.94 ± 7.94	−0.173 (0.865)
MMSE-K (score)	26.75 ± 0.71	27.00 ± 0.82	−0.636 (0.536)
Gender (male/female)	3/5	4/3	0.579 (0.447)
Onset (month)	7.50 ± 7.55	7.71 ± 7.55	−0.548 (0.593)

Affected side (right/left)			
Stroke type	4/4	5/2	0.714 (0.398)
(Ischemic/Hemorrhagic)			

Note: ^a Mean $\pm$ SD, ^b Chi-square test, and ^c independent t-test. MMSE, Mini-Mental State Examination.

Changes in motor function following the intervention

Both the experimental and control groups exhibited statistically significant improvements in motor function from pre- to post-training. Analysis of Fugl-Meyer Assessment scores revealed a significant within-group

difference, with greater gains observed in the experimental group ($P < 0.05$). Between-group comparison of pre-to-post changes in Fugl-Meyer Assessment scores also showed a statistically significant advantage for the experimental group ($P < 0.05$) (Table 2).

Table 2. Change in motor function according to intervention.

		Experimental group (n = 8)	Control group (n = 7)	z	P
FMA	Pre	21.62 $\pm$ 2.13 ^a	20.57 $\pm$ 1.98		
	Post	26.37 $\pm$ 0.74	22.14 $\pm$ 1.95		
	Post-Pre	4.75 $\pm$ 1.58	1.57 $\pm$ 0.53	-3.105	0.002 *
	z (p)	-2.552 (0.011 *)	-2.428 (0.015 *)		

Note. ^a Mean $\pm$ SD; FMA: Fugl-Meyer Assessment; and * $P < 0.05$.

Changes in balance following the intervention

Both groups displayed statistically significant improvements in balance measures between pre- and post-training assessments. Comparison of pre- and post-test changes in Berg Balance Scale (BBS) and Timed Up

and Go (TUG) scores showed that the experimental group achieved significantly greater improvements than the control group ($P < 0.05$). Between-group analysis of the magnitude of change in BBS and TUG scores further confirmed a statistically significant advantage for the experimental group ($P < 0.05$) (Table 3).

Table 3. Change in balance according to intervention.

		Experimental group (n = 8)	Control group (n = 7)	z	P
BBS	Pre	44.50 $\pm$ 2.72 ^a	44.14 $\pm$ 2.41		
	Post	47.50 $\pm$ 2.56	45.85 $\pm$ 1.86		
	Post-Pre	3.00 $\pm$ 0.75	1.71 $\pm$ 0.95	-2.304	0.021 *
	z (p)	-2.558 (0.011 *)	-2.414 (0.016 *)		
TUG	Pre	16.19 $\pm$ 1.68	17.19 $\pm$ 1.73		
	Post	13.09 $\pm$ 1.15	16.07 $\pm$ 1.77		
	Post-Pre	-3.10 $\pm$ 1.60	-1.12 $\pm$ 0.43	-3.125	0.002 *
	z (p)	-2.521 (0.012 *)	-2.366 (0.018 *)		

Note. ^a Mean $\pm$ SD, BBS: Berg balance scale, TUG: timed up and go test, and * $P < 0.05$.

Alterations in spatiotemporal gait variables after the intervention

Pre- and post-training evaluations revealed notable improvements in spatiotemporal gait characteristics across both groups. Changes in affected step length (ASL), stride length (SL), affected single support phase

(ASS), and cadence showed that the experimental group made markedly greater progress than the control group ($P < 0.05$). Inter-group analysis of the extent of change in these ASL, SL, ASS, and cadence measures likewise indicated a statistically meaningful benefit for the experimental group ($P < 0.05$) (Table 4).

Table 4. Change in spatiotemporal gait parameters according to intervention.

		Experimental group (n = 8)	Control group (n = 7)	z	P
ASL	Pre	41.87 $\pm$ 6.85 ^a	43.97 $\pm$ 7.47		
	Post	47.22 $\pm$ 6.95	45.98 $\pm$ 7.14		
	Post-Pre	5.35 $\pm$ 3.26	2.01 $\pm$ 1.23	-2.609	0.009 *
	z (p)	-2.524 (0.012 *)	-2.366 (0.018 *)		

SL	Pre	64.22 ± 7.71	68.47 ± 8.93		
	Post	68.08 ± 7.41	70.22 ± 7.89		
	Post-Pre	3.86 ± 2.07	1.75 ± 1.34	-2.269	0.023 *
	z (p)	-2.524 (0.012 *)	-2.384 (0.017 *)		
ASS	Pre	34.65 ± 3.22	36.37 ± 1.94		
	Post	37.26 ± 2.40	37.60 ± 2.31		
	Post-Pre	2.61 ± 1.35	1.22 ± 0.72	-2.027	0.043 *
	z (p)	-2.521 (0.012 *)	-2.366 (0.018 *)		
Cadence	Pre	0.74 ± 0.10	0.70 ± 0.07		
	Post	0.81 ± 0.07	0.73 ± 0.08		
	Post-Pre	0.07 ± 0.04	0.02 ± 0.03	-2.296	0.022 *
	z (p)	-2.546 (0.011 *)	-1.706 (0.088)		

^a Mean ± SD, ASL: affected step length, SL: step length, ASS: affected single support, and * P < 0.05.

The overarching objective in stroke rehabilitation is to help patients regain the ability to walk and carry out daily tasks without assistance. This investigation examined how a virtual reality (VR) walking program incorporating real-time feedback influences lower limb motor function, balance, and spatiotemporal gait measures in individuals with chronic stroke. The trial involved 15 chronic stroke patients who participated in 30-minute sessions three times per week for five weeks. The study specifically assessed the value of treadmill-based gait training enhanced by real-time VR feedback. Key outcomes showed that the experimental group achieved substantially better gains in motor function, balance, and gait performance than the control group.

Although both groups improved across all measured domains, the experimental group demonstrated markedly superior results in motor function. This aligns with findings from Anwar *et al.* [38], who studied 68 stroke patients receiving VR combined with conventional therapy three times weekly for six weeks. Their VR group showed notable improvements in Fugl-Meyer motor scores, reduced joint pain, and increased range of motion compared with the conventional therapy group. Likewise, Yaman *et al.* [39] reported on 60 patients with chronic stroke, in which the experimental arm (30 minutes of VR followed by 30 minutes of standard therapy) outperformed the control arm (60 minutes of standard therapy alone) on lower extremity Fugl-Meyer scores and balance measures. These outcomes are consistent with the present research.

Such improvements likely stem from real-time feedback VR training, which promotes better weight distribution and activates hip-region musculature, thereby enhancing lower limb motor control. Integrating this with treadmill walking provides concurrent sensory stimulation, directs

attention to essential walking cues, and strengthens lower extremity muscles, thereby supporting functional recovery.

Overall, the current findings demonstrate that a real-time feedback VR walking program effectively enhances motor function, balance, and gait in patients with chronic stroke. These results offer valuable baseline information for designing future rehabilitation strategies for this population.

Regarding balance, both groups improved, but the experimental group improved significantly more than the control group. Karasu *et al.* implemented Nintendo Wii-based balance training with 23 participants selected from 70 stroke patients. The control group received standard physical therapy, occupational therapy, and neurodevelopmental treatment. Both arms underwent 8 weeks of intervention, five days per week, lasting 2–3 hours daily. The Wii training used the Balance Board to monitor weight and center of pressure, deliver movement feedback, and incorporate six of nine available balance exercises. The experimental group achieved statistically significant gains in Berg Balance Scale (BBS), Functional Reach Test (FRT), Timed Up and Go (TUG), Postural Assessment Scale for Stroke (PASS), and Static Balance Index.

In research by Porras *et al.*, 167 individuals across six diagnostic categories (Parkinson's disease: 36, stroke: 31, multiple sclerosis: 9, traumatic brain injury: 10, other neurological conditions: 42, and non-neurological: 39) completed 12 sessions focused on balance, gait, and cognition, each lasting 30–45 minutes. Several sessions incorporated virtual reality more than twice. Interventions were personalized and included task-specific practice, sensory feedback, and motor relearning

via VR. Significant enhancements were recorded in the 10-meter walk test, TUG, and BBS.

Silva *et al.* [40] compared real-world and virtual reality walking in 10 stroke patients during a 3-minute stationary walking task. Results indicated superior performance in VR, particularly for cadence and ankle dorsiflexion angle. Cho and Lee [41] studied 30 patients with chronic stroke and compared non-immersive VR treadmill training with standard treadmill training over 6 weeks (three 30-minute sessions per week). The VR group viewed videos of real-environment walking while on the treadmill. Significant improvements occurred in dynamic balance (BBS and TUG) and temporal gait parameters (speed, cadence, single- and double-limb support times), as well as spatial parameters (step length and stride length). Between-group differences favored the VR approach for BBS, TUG, gait speed, cadence, single-limb support, step length, and stride length.

Enam *et al.* applied augmented reality treadmill training to two stroke patients over 4 weeks (3 sessions per week), with assessments at baseline, post-intervention, and 1-month follow-up. Notable gains were observed in BBS, 10-meter walk test, and 6-minute walk test. These outcomes suggest that treadmill training strengthens lower limbs, while real-time feedback facilitates smoother weight transfer to the affected side, thereby enhancing balance and walking speed.

Moreover, repeated practice and consistent effort during real-time feedback VR treadmill training bolster motor learning. This approach also improves stance-phase stability on the affected limb, promoting effective weight shifting and optimizing spatiotemporal gait features.

Several limitations should be acknowledged. First, participants were restricted to chronic stroke patients meeting specific eligibility criteria, limiting generalizability to the broader stroke population. Second, adaptation time to the VR headset differed among individuals, and some sessions were paused due to dizziness. Third, both groups received standard physical therapy alongside the study interventions, which may have influenced the results. Fourth, the small sample ($n = 15$) and lack of detailed analysis regarding stroke severity and spasticity levels limit interpretation. Subsequent research should recruit larger cohorts and incorporate spasticity evaluations to strengthen the evidence base for VR interventions in stroke rehabilitation.

Looking ahead, overcoming these constraints could expand real-time feedback VR programs beyond balance

training to include diverse task-oriented and dual-task walking exercises. Such programs could benefit patients with varied lesion locations, extending beyond chronic stroke cases. Currently, the scarcity of dedicated VR medical devices and rehabilitation protocols underscores the need for continued development and investigation in this field.

Conclusion

This study evaluated the impact of combining treadmill gait training with real-time feedback virtual reality on lower extremity motor function, balance, and walking performance. Results showed that the VR-enhanced treadmill approach produced greater improvements in motor function, balance, and gait than treadmill training alone. Consequently, this method holds promise as an effective component of comprehensive rehabilitation programs designed to restore motor function, balance, and ambulation in post-stroke individuals.

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