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EFFECTIVENESS OF DUAL-TASK VIRTUAL REALITY TRAINING ON BALANCE, GAIT PERFORMANCE, AND COGNITIVE FUNCTION IN INDIVIDUALS WITH STROKE: A RANDOMIZED CONTROLLED TRIAL

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ABSTRACT

Background: *Stroke frequently results in persistent impairments in balance, gait, and cognitive function, limiting functional independence and quality of life. Although virtual reality (VR) has emerged as a promising rehabilitation approach, evidence regarding the effectiveness of dual-task VR training integrating simultaneous motor and cognitive activities remains limited.*

Objective: *To evaluate the effectiveness of dual-task virtual reality training combined with conventional physiotherapy on balance, gait performance, and cognitive function in individuals with stroke.*

Methods: *A single-center randomized controlled trial was conducted involving 46 individuals with stroke who met the eligibility criteria. Participants were randomly allocated to either the experimental group (dual-task VR training plus conventional physiotherapy; n = 23) or the control group (conventional physiotherapy alone; n = 23). Both groups received supervised rehabilitation for 8 weeks. Balance was assessed using the Berg Balance Scale (BBS), functional mobility using the Timed Up and Go (TUG) test, gait performance using the 10-Meter Walk Test (10MWT), and cognitive function using the Montreal Cognitive Assessment (MoCA). Data was analyzed using paired and independent t-tests, while between-group differences were evaluated using analysis of covariance (ANCOVA). Statistical significance was set at $p < 0.05$.*

Results: *Both groups demonstrated significant improvements following the intervention; however, participants receiving dual-task VR training achieved significantly greater improvements in BBS, TUG, 10MWT, and MoCA scores compared with the conventional physiotherapy group (all* $p < 0.001$*). ANCOVA confirmed significant between-group treatment effects across all primary outcome measures after adjusting for baseline values.*

Conclusion: *Dual-task virtual reality training combined with conventional physiotherapy was more effective than conventional physiotherapy alone in improving balance, gait performance, functional mobility, and cognitive function in individuals with stroke. Incorporating cognitive and motor tasks within an interactive virtual environment may represent an effective strategy for enhancing post-stroke rehabilitation. Larger multicenter randomized controlled trials with longer follow-up are recommended to confirm these findings.*

Keywords: *Stroke; Virtual reality; Dual-task training; Balance; Gait; Cognitive function; Randomized controlled trial; Neurorehabilitation.*

Introduction

Stroke remains one of the leading causes of long-term disability and mortality worldwide, placing a substantial burden on individuals, healthcare systems, and society. According to the Global Burden of Disease Study, stroke continues to rank among the foremost causes of disability-adjusted life years, with increasing incidence and prevalence attributable to population aging, sedentary lifestyles, hypertension, diabetes mellitus, and other vascular risk factors. Although advances in acute stroke management have improved survival rates, a considerable proportion of survivors experience persistent physical, cognitive, and psychosocial impairments that significantly limit functional independence and quality of life. Consequently, optimizing rehabilitation strategies has become an essential component of post-stroke care aimed at restoring function and reducing long-term disability (1).

Among the numerous impairments following stroke, deficits in balance, gait, and cognitive function are particularly prevalent and have profound effects on an individual's ability to perform activities of daily living independently. Damage to cortical and subcortical motor pathways frequently results in muscle weakness, impaired motor coordination, abnormal muscle tone, reduced postural stability, and asymmetrical weight distribution. These impairments compromise static and dynamic balance, thereby increasing the likelihood of falls, restricting community mobility, and limiting participation in social and occupational activities (2). Persistent balance dysfunction has been identified as one of the strongest predictors of functional dependence and recurrent falls in stroke survivors, emphasizing the need for rehabilitation approaches that specifically target postural control.

Gait impairment represents another major consequence of stroke rehabilitation. Approximately half of stroke survivors continue to exhibit walking limitations even after completing conventional rehabilitation. Common gait abnormalities include reduced walking speed, shortened step length, prolonged double-support time, decreased cadence, poor weight transfer, and impaired interlimb coordination. These abnormalities reduce walking efficiency and increase energy expenditure, making community ambulation challenging. Furthermore, impaired gait contributes directly to reduced participation in daily activities and diminished quality of life. Restoration of safe, efficient, and adaptable walking therefore remains one of the primary goals of neurological rehabilitation programs (3).

In addition to motor deficits, cognitive impairments frequently accompany stroke and substantially influence rehabilitation outcomes. Deficits involving attention, executive function, working memory, processing speed, and cognitive flexibility are commonly observed, even among individuals who demonstrate satisfactory motor recovery. Executive dysfunction interferes with planning, problem-solving, environmental adaptation, and the execution of complex motor activities, thereby compromising independence in daily living. These cognitive deficits also reduce patients' ability to participate effectively in rehabilitation sessions, ultimately slowing functional recovery and increasing caregiver burden (4).

The relationship between motor and cognitive dysfunction has become increasingly recognized in modern neurorehabilitation. Daily activities rarely involve isolated motor tasks; instead, they require simultaneous execution of motor and cognitive processes. Walking while conversing, avoiding environmental obstacles, carrying objects, navigating unfamiliar surroundings, or responding to external stimulus all demand concurrent cognitive processing. Following stroke, limited attentional capacity and impaired executive control reduce the ability to perform such simultaneous tasks effectively, resulting in cognitive-motor interference commonly referred to as dual-task interference. During dual-task performance, deterioration may occur in motor performance, cognitive performance, or both, thereby increasing fall risk and reducing functional mobility (5).

Dual-task deficits are increasingly regarded as clinically relevant indicators of functional disability after stroke because they closely resemble the challenges encountered during real-life community ambulation. Traditional rehabilitation programs generally emphasize isolated motor practice under controlled clinical conditions, whereas real-world environments continuously require simultaneous management of cognitive and motor demands. Consequently, improvements achieved under single-task conditions may not fully translate into functional independence during community participation. Rehabilitation approaches that integrate simultaneous cognitive and motor challenges have therefore attracted growing attention as potentially more effective strategies for improving everyday function (6).

Dual-task training involves the simultaneous performance of motor and cognitive activities with the objective of enhancing attentional allocation, executive processing, motor automaticity, and overall functional performance. The theoretical foundation of dual-task rehabilitation is based on principles of neuroplasticity and motor learning, suggesting that repetitive practice under cognitively demanding conditions promotes cortical reorganization and strengthens neural networks involved in sensorimotor integration. Improvements achieved through dual-task interventions may therefore extend beyond isolated motor recovery by enhancing the individual's ability to perform complex functional activities safely and efficiently (7).

Recent systematic reviews and meta-analyses have demonstrated that dual-task training significantly improves balance, gait speed, cadence, and postural stability compared with conventional rehabilitation in individuals with stroke. Moderate improvements have also been reported in functional mobility and dynamic balance measures, suggesting that dual-task interventions facilitate more efficient integration of cognitive and motor processes during movement. Nevertheless, the magnitude of these improvements varies considerably across studies due to differences in intervention protocols, training intensity, outcome measures, and participant characteristics (8). (Sage Journals)

Conventional physiotherapy remains the cornerstone of stroke rehabilitation and includes task-oriented training, gait re-education, balance exercises, strengthening, proprioceptive training, and functional mobility practice. While these interventions have demonstrated effectiveness in improving motor function, several limitations have been identified. Repetitive exercise routines may reduce patient engagement, treatment intensity is often limited by therapist availability, and many conventional interventions provide insufficient cognitive stimulation. Furthermore, standard rehabilitation may inadequately prepare patients for complex real-world situations that require simultaneous cognitive processing during movement (9).

The emergence of virtual reality (VR) technology has introduced new opportunities for enhancing neurorehabilitation. Virtual reality enables users to interact with computer-generated environments that simulate meaningful real-life activities through visual, auditory, and sometimes haptic feedback. These immersive or semi-immersive environments facilitate repetitive, task-oriented practice while maintaining high levels of motivation and engagement through gamification. Real-time feedback, adjustable task difficulty, multisensory stimulation, and individualized progression make VR particularly suitable for promoting motor learning and neuroplasticity following stroke (10).

A comprehensive systematic review and meta-analysis by Zhang et al. demonstrated that virtual reality interventions significantly improved lower-limb motor function, balance, gait performance, and activities of daily living among individuals with stroke compared with conventional rehabilitation. However, evidence regarding improvements in cognitive outcomes remained inconclusive, highlighting the need for rehabilitation approaches that deliberately integrate cognitive challenges within virtual environments rather than focusing solely on motor practice (11).

Likewise, an umbrella systematic review evaluating multiple systematic reviews concluded that virtual reality consistently improved balance, gait, limb motor function, and functional independence after stroke, although the certainty of evidence ranged from very low to moderate. The review further emphasized considerable heterogeneity in intervention protocols and recommended additional high-quality randomized controlled trials employing standardized methodologies and clinically meaningful outcome measures (12).

Recent advances in neurorehabilitation have shifted the emphasis from isolated motor training toward interventions that simultaneously challenge cognitive and motor systems. This transition is supported by the understanding that recovery after stroke depends not only on regaining muscle strength and motor control but also on restoring the integration of sensorimotor and cognitive networks. Virtual reality (VR) has emerged as an innovative rehabilitation technology capable of delivering enriched, task-oriented, and multisensory environments that closely replicate real-life activities while providing real-time feedback and high-intensity repetitive practice. Such characteristics make VR particularly suitable for promoting experience-dependent neuroplasticity and motor relearning following stroke (13).

Virtual reality-based rehabilitation operates on established principles of motor learning, including repetitive practice, augmented sensory feedback, goal-directed activities, progressive task difficulty, and patient engagement. Unlike conventional rehabilitation, VR enables individuals to interact with dynamic virtual environments that require continuous adaptation of postural responses, limb coordination, and decision-making. Immediate visual and auditory feedback facilitates error correction and reinforces successful motor performance, thereby enhancing cortical reorganization and functional recovery. Furthermore, the enjoyable and game-like nature of VR improves motivation, adherence, and treatment intensity, which are recognized determinants of successful neurological rehabilitation (13).

Although numerous studies have demonstrated the benefits of VR for improving motor recovery after stroke, many interventions have primarily focused on single-task motor performance. Conventional VR protocols often involve balance games, obstacle avoidance, reaching activities, or gait practice without deliberately incorporating cognitive demands. However, successful performance of everyday activities requires continuous interaction between motor execution and higher cognitive functions, particularly attention, executive control, working memory, and information processing. Consequently, integrating cognitive tasks into VR-based rehabilitation has become an important area of investigation in contemporary stroke rehabilitation research (14).

Dual-task virtual reality training combines simultaneous motor and cognitive activities within an interactive virtual environment. During training, participants perform balance or gait tasks while concurrently completing cognitive challenges such as arithmetic calculations, memory recall, selective attention, obstacle identification, verbal fluency, or decision-making tasks. This approach is intended to improve automaticity of movement while strengthening attentional allocation and executive control mechanisms. The simultaneous activation of motor and cognitive neural networks is believed to facilitate greater cortical plasticity than motor practice alone, thereby enhancing functional recovery and improving performance under real-world conditions (13).

The neurophysiological rationale for dual-task VR training is supported by evidence demonstrating that motor and cognitive processes share overlapping neural substrates involving the prefrontal cortex, supplementary motor area, basal ganglia, cerebellum, and parietal cortex. Stroke-related disruption of these interconnected networks reduces attentional capacity and impairs automatic motor control, resulting in cognitive-motor interference during everyday activities. Repeated practice under dual-task conditions is thought to improve neural efficiency, facilitate adaptive cortical reorganization, strengthen sensorimotor integration, and enhance coordination between executive and motor control systems. These adaptations may contribute to improvements in balance control, walking performance, and cognitive function simultaneously (13).

Growing clinical evidence supports the incorporation of VR into stroke rehabilitation. A systematic review and meta-analysis by Hao et al. found that VR-based rehabilitation was a feasible and effective intervention during the early stage of stroke recovery and produced functional outcomes comparable to or better than conventional rehabilitation across several domains. The authors emphasized that VR provided a safe environment for intensive repetitive practice while maintaining patient motivation through interactive activities, although improvements in cognition remained inconsistent across studies (13).

Similarly, Cardile, D et al. (2025) reported that combining VR with conventional rehabilitation significantly improved global cognition, executive function, motor performance, mood, and activities of daily living in individuals with chronic stroke. Their meta-analysis highlighted that interventions integrating cognitive engagement with motor practice produced greater improvements than traditional rehabilitation alone, suggesting that cognitive stimulation should be considered an essential component of post-stroke rehabilitation programs (14).

More recently, an updated Cochrane systematic review evaluating 72 randomized and quasi-randomized trials concluded that VR combined with standard rehabilitation produced modest improvements in balance, activity limitations, and functional recovery compared with alternative therapies. Nevertheless, the review found insufficient evidence regarding cognitive outcomes and emphasized substantial variability in intervention protocols, VR systems, treatment dosage, and methodological quality across studies. The authors recommended well-designed randomized controlled trials using standardized interventions and clinically relevant outcome measures to strengthen the evidence base (10).

Evidence regarding dual-task rehabilitation has also expanded considerably. A recent systematic review and meta-analysis published in 2025 demonstrated that dual-task exercise training significantly improved motor function and several cognitive outcomes in individuals with stroke compared with single-task rehabilitation. However, the review reported considerable heterogeneity among included studies with respect to participant characteristics, intervention protocols, training duration, outcome measures, and methodological quality. Furthermore, only a limited number of studies specifically investigated VR-based dual-task interventions, highlighting an important gap in current literature (12, 14).

Despite encouraging findings, several limitations remain within the existing evidence. Many published studies have evaluated either conventional dual-task training or VR-based motor rehabilitation independently rather than combining both approaches into a structured dual-task VR intervention. Sample sizes have frequently been small, follow-up periods have often been short, and intervention protocols have varied substantially in terms of immersion level, cognitive task complexity, treatment intensity, and outcome assessment. Moreover, most studies have emphasized motor recovery while giving comparatively less attention to simultaneous improvements in cognition and functional dual-task performance. These methodological inconsistencies limit the generalizability of existing findings and prevent definitive conclusions regarding the clinical superiority of dual-task VR training over conventional rehabilitation (11).

Given these limitations, further high-quality randomized controlled trials employing standardized intervention protocols and comprehensive assessments of balance, gait, and cognitive function are warranted. Evaluating these domains concurrently is particularly important because successful community ambulation depends upon efficient interaction between motor and cognitive systems. Establishing the effectiveness of dual-task VR training may provide clinicians with evidence-based rehabilitation strategies capable of improving functional independence, reducing fall risk, and enhancing quality of life among individuals recovering from stroke.

Despite the growing body of evidence supporting virtual reality (VR) and dual-task interventions in stroke rehabilitation, several important knowledge gaps remain. First, most published randomized controlled trials have investigated either conventional dual-task training or VR-based motor rehabilitation independently, while relatively few studies have evaluated the combined effect of dual-task training delivered within a virtual reality environment. Second, considerable heterogeneity exists through previous studies regarding the type of VR system used, intervention intensity, duration of treatment, cognitive task complexity, and outcome measures, making direct comparison and clinical interpretation difficult. Third, although improvements in balance and gait have frequently been reported, cognitive outcomes have been evaluated less consistently despite their critical role in safe community ambulation and functional independence. Furthermore, many studies have included relatively small sample sizes, short intervention periods, and limited follow-up, thereby reducing the generalizability of their findings. Recent systematic reviews have emphasized the need for rigorously designed randomized controlled trials employing standardized dual-task VR protocols and comprehensive assessment of both motor and cognitive outcomes to establish stronger clinical evidence for this emerging rehabilitation approach (10).

From a neuro-rehabilitation perspective, effective recovery after stroke depends on restoring the coordinated interaction between cognitive and motor systems rather than improving isolated physical performance. Activities encountered in daily life, such as walking while conversing, negotiating obstacles, carrying objects, or responding to environmental distractions, require continuous allocation of attention and executive control. Rehabilitation programs that focus exclusively on motor performance may therefore provide limited transfer to real-world functional activities. Dual-task virtual reality training offers an innovative therapeutic approach by simultaneously challenging postural control, gait adaptability, attention, working memory, and executive function within safe and interactive virtual environments. Such interventions may promote greater neuroplastic adaptation through repetitive, goal-directed, and cognitively demanding practice, ultimately improving functional mobility and independence.

Recent systematic reviews have reported encouraging evidence regarding the effectiveness of VR-based rehabilitation and dual-task interventions individually. However, conclusive evidence regarding their combined application remains insufficient because of methodological variability and the limited availability of high-quality randomized controlled trials. Consequently, further investigation is required to determine whether integrating cognitive challenges into virtual reality rehabilitation provides superior improvements in balance, gait performance, and cognitive function compared with conventional rehabilitation strategies (10).

The present study was therefore designed to evaluate the effectiveness of dual-task virtual reality training on balance, gait, and cognitive function in individuals with stroke using a randomized controlled trial design. By simultaneously assessing motor and cognitive outcomes, this study seeks to provide robust evidence regarding the clinical value of integrating dual-task principles with virtual reality technology in contemporary stroke rehabilitation. The findings may contribute to the development of evidence-based rehabilitation protocols that improve functional recovery, reduce fall risk, enhance community participation, and ultimately improve the quality of life of stroke survivors.

Aim of the Study

To determine the effectiveness of dual-task virtual reality training on balance, gait, and cognitive function in individuals with stroke.

Objectives

Primary Objective

- To determine the effect of dual-task virtual reality training on balance in individuals with stroke.

Secondary Objectives

- To evaluate the effect of dual-task virtual reality training on gait performance and functional mobility in individuals with strokes.
- To assess the effect of dual-task virtual reality training on cognitive function in individuals with stroke.
- To compare post-intervention outcomes between participants receiving dual-task virtual reality training and those receiving conventional rehabilitation.

Research Hypotheses

Null Hypothesis (H_0)

There is no statistically significant difference in balance, gait performance, or cognitive function between individuals with stroke receiving dual-task virtual reality training and those receiving conventional rehabilitation.

Alternative Hypothesis (H_1)

Dual-task virtual reality training produces significantly greater improvements in balance, gait performance, and cognitive function compared with conventional rehabilitation in individuals with stroke.

Methodology

Study Design

This study was conducted as a prospective, parallel-group, assessor-blind randomized controlled trial to evaluate the effectiveness of dual-task virtual reality (VR) training on balance, gait, and cognitive function in individuals with stroke. The study followed the Consolidated Standards of Reporting Trials (CONSORT) guidelines for randomized controlled trials. Ethical approval was obtained from the Institutional Review Board/Ethics Committee before commencement of the study, and all participants provided written informed consent prior to enrollment.

Study Setting

The study was carried out in the Department of Physical Therapy at Paraplegic Centre Peshawar. Participant recruitment and intervention were conducted within the outpatient neurorehabilitation unit, where standardized assessment and treatment facilities were available.

Study Population

The study population consisted of individuals diagnosed with stroke who were referred to for physiotherapy rehabilitation.

Eligibility Criteria

Inclusion Criteria

Participants were included if they:

- Adults aged 40–75 years.
- had a confirmed diagnosis of ischemic or hemorrhagic stroke based on clinical and neuroimaging findings;
- Subacute stroke (3–12 months)
- were medically stable;
- were able to stand independently or with minimal assistance;
- were able to walk with or without an assistive device for a specified distance;
- could follow verbal instructions;
- demonstrated adequate vision and hearing to participate in virtual reality activities;
- provided written informed consent.

Exclusion Criteria

Participants were excluded if they:

- had severe cognitive impairment that interfered with participation;
- had severe aphasia preventing communication;
- had other neurological disorders affecting balance or gait;
- had significant musculoskeletal conditions limiting lower limb function;
- had severe visual or vestibular disorders;
- had unstable cardiovascular conditions;
- had uncontrolled epilepsy or any contraindication to virtual reality exposure;
- were currently participating in another structured rehabilitation trial.

Sample Size

The required sample size was calculated using G*Power version 3.1.9.7 based on the primary outcome (Berg Balance Scale), assuming an effect size of 0.80, a significance level (α) of 0.05, and statistical power ($1-\beta$) of 80%. The minimum required sample size was 46 participants (23 per group).

Sampling Technique

Participants were recruited using consecutive sample samples until the required sample size was achieved. All eligible participants who fulfilled the inclusion criteria during the recruitment period were invited to participate.

Randomization

After baseline assessment, participants were randomly allocated to either the experimental group (dual-task virtual reality training plus conventional physiotherapy) or the control group (conventional physiotherapy alone or conventional dual-task training, depending on the study protocol). Random allocation was generated using a simple randomization sequence prepared by an independent researcher who was not involved in participant recruitment, assessment, or treatment.

Allocation Concealment

Allocation concealment was ensured using sequentially numbered, opaque, sealed envelopes prepared by an independent investigator. The envelopes were open only after completion of baseline assessment.

Blinding

Due to the nature of rehabilitation interventions, participant and therapist blinding was not feasible. However, the outcome assessor remained blinded to group allocation throughout the study. The statistician performing data analysis was also blinded to treatment allocation until completion of statistical analyses.

Intervention

Participants in both groups received supervised rehabilitation sessions over the 8-week intervention period. The experimental group received dual-task virtual reality (VR) training in addition to conventional physiotherapy, whereas the control group received conventional physiotherapy alone. All intervention sessions were delivered by licensed physiotherapists experienced in neurological rehabilitation. The detailed intervention protocol, including treatment components, session duration, frequency, progression, and supervision, is presented in Table 1.

Table 1. Intervention Protocol

Component	Experimental Group (Dual-Task Virtual Reality + Conventional Physiotherapy)	Control Group (Conventional Physiotherapy)
Intervention duration	8 weeks	8 weeks
Session frequency	3 sessions per week	3 sessions per week
Session duration	60 minutes	60 minutes
Warm-up	10 minutes of range of motion, stretching, and mobility exercises	10 minutes of range of motion, stretching, and mobility exercises

Main intervention	30 minutes of conventional physiotherapy followed by 20 minutes of dual-task virtual reality training	50 minutes of conventional physiotherapy
Conventional physiotherapy	Balance training, gait training, lower-limb strengthening, weight-shifting, transfer training, sit-to-stand practice, functional mobility, and postural control exercises	Balance training, gait training, lower-limb strengthening, weight-shifting, transfer training, sit-to-stand practice, functional mobility, and postural control exercises
Dual-task VR training	Interactive VR-based balance and gait exercises performed simultaneously with cognitive tasks (e.g., arithmetic calculations, memory recall, obstacle identification, color recognition, selective attention, verbal fluency, and decision-making) with real-time visual and auditory feedback	Not applicable
Progression	Exercise difficulty progressively increased by modifying balance demands, gait complexity, cognitive task difficulty, and movement speed according to participant performance	Exercise intensity and complexity progressed according to participant tolerance and clinical improvement
Supervision	All sessions supervised by a licensed physiotherapist experienced in neurological rehabilitation	All sessions supervised by a licensed physiotherapist experienced in neurological rehabilitation
Safety measures	Therapist guarding provided during challenging balance and gait activities; rest breaks allowed as needed	Therapist guarding provided during challenging balance and gait activities; rest breaks allowed as needed

Outcome Measures

Outcome assessments were performed at baseline and after completion of the intervention period by an assessor who remained blinded to group allocation.

Primary Outcome

Balance

Balance was assessed using the Berg Balance Scale (BBS), a valid and reliable 14-item clinical measure widely used to evaluate static and dynamic balance in individuals with stroke. The total score ranges from 0 to 56, with higher scores indicating better balanced performance and a lower risk of falls.

Secondary Outcomes

Gait Performance

Gait performance was evaluated using the following standardized clinical outcome measures:

- **Timed Up and Go Test (TUG):** Used to assess functional mobility and dynamic balance. Participants were instructed to stand from a chair, walk three meters, turn around, return to the chair, and sit down. The time required to complete the task was recorded in seconds, with shorter times indicating better mobility.
- **10-Meter Walk Test (10MWT):** Used to evaluate comfortable walking speed. Participants walked 10 meters at their normal pace, and gait speed was calculated in meters per second (m/s). Higher walking speeds indicated better gait performance.

Cognitive Function

Cognitive function was assessed using the Montreal Cognitive Assessment (MoCA), a validated screening tool designed to evaluate multiple cognitive domains, including attention, executive function, memory, language, visuospatial ability, abstraction, delayed recall, and orientation. Total scores range from 0 to 30, with higher scores indicating better cognitive function.

Data Collection Procedure

Potential participants were screened for eligibility according to the predefined inclusion and exclusion criteria. Eligible participants were informed about the objectives, procedures, potential benefits, and possible risks of the study. Written informed consent was obtained before enrollment.

Baseline demographic and clinical information, including age, sex, type of stroke, affected side, duration since stroke, comorbidities, and assistive device use, were recorded.

Following baseline assessment, participants were randomized into either the experimental or control group. Both groups completed their assigned intervention according to the study protocol.

Outcome assessments were performed before commencement of treatment and immediately after completion of the intervention period. All assessments were conducted by the same blind physiotherapist using standardized testing procedures.

Data Management

Data was recorded using standardized case report forms and entered a password-protected electronic database. Double data entry and verification procedures were employed to minimize transcription errors. Participant confidentiality was maintained throughout the study by assigning unique identification codes.

Statistical Analysis

Data was analyzed using IBM Statistical Package for the Social Sciences (SPSS) version 27.0. Continuous variables were expressed as mean ± standard deviation (SD), while categorical variables were presented as frequencies and percentages. Normality of continuous variables was assessed using the Shapiro–Wilk test. Baseline characteristics between the two groups were compared using the independent samples *t*-test for continuous variables and the Chi-square test for categorical variables. Within-group changes from baseline to post-intervention were analyzed using the paired *t*-test. Between-group treatment effects were evaluated using analysis of covariance (ANCOVA), with post-intervention scores as the dependent variable, treatment group as the fixed factor, and baseline scores as covariates. A two-tailed *p*-value < 0.05 was considered statistically significant.

Results

Participant Flow

A total of 58 individuals were assessed for eligibility, of whom 46 met the inclusion criteria and were enrolled in the study. The required sample size was determined a priori using G*Power software. Eligible participants were randomly allocated in a 1:1 ratio to either Group A (Dual-Task Virtual Reality Training + Conventional Physiotherapy; n = 23) or Group B (Conventional Physiotherapy; n = 23). All participants completed the 8-week intervention and the post-intervention assessments. No participants were lost to follow-up or discontinued the intervention; therefore, all randomized participants were included in the final statistical analysis using the intention-to-treat population. The participant recruitment, randomization, allocation, follow-up, and analysis process is presented in Figure 1.

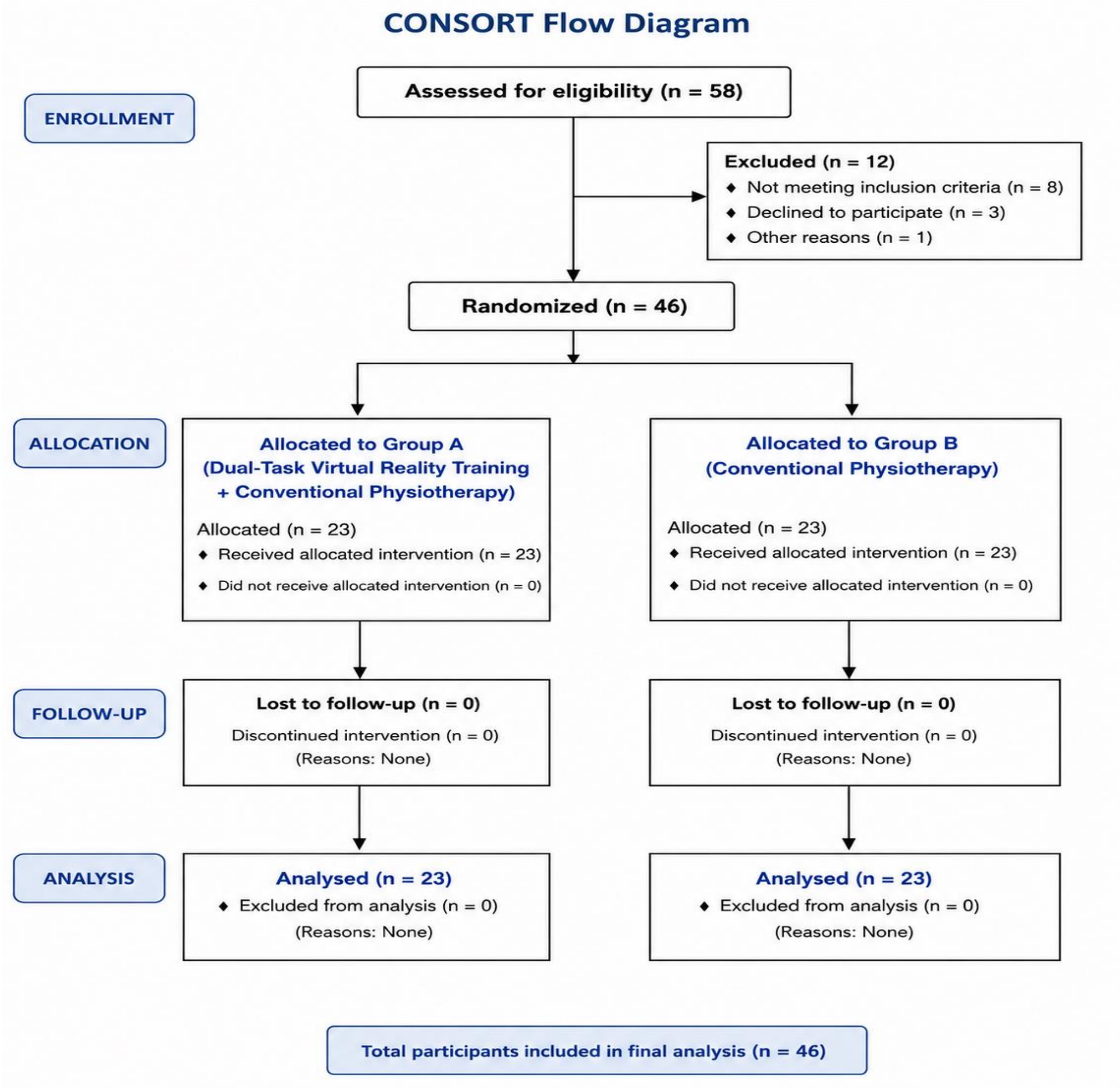

Figure 1. *CONSORT Flow Diagram of Participant Recruitment and Follow-up*

Baseline Characteristics

Baseline demographic and clinical characteristics of the participants are presented in Table 2. There were no statistically significant differences between the experimental and control groups regarding age (p = 0.307), sex distribution (p = 1.000), body mass index (p = 0.571), duration since stroke (p = 0.117), or stroke subtype (p = 0.326), indicating that the two groups were comparable at baseline.

Table 2. Baseline Demographic and Clinical Characteristics

Variable	Group A (n = 23)	Group B (n = 23)	p-value
Age (years)	56.9 ± 8.5	59.4 ± 7.9	0.307
Male, n (%)	12 (52.2)	12 (52.2)	1.000
Female, n (%)	11 (47.8)	11 (47.8)	—
BMI (kg/m²)	26.7 ± 3.2	27.3 ± 3.9	0.571

Duration since stroke (months)	7.3 ± 2.6	8.6 ± 2.9	0.117
Ischemic stroke, n (%)	18 (78.3)	15 (65.2)	0.326
Hemorrhagic stroke, n (%)	5 (21.7)	8 (34.8)	—

Balance Outcome (Berg Balance Scale)

Both groups demonstrated significant improvements in balance following the intervention. There was no statistically significant difference in baseline Berg Balance Scale scores between the two groups (34.8 ± 4.6 vs. 35.2 ± 4.9; p = 0.779), indicating comparable balance status before treatment. After completion of the intervention, the experimental group achieved significantly higher post-treatment BBS scores than the control group (47.5 ± 4.1 vs. 41.4 ± 4.6; p < 0.001). The mean improvement in BBS was also significantly greater in the experimental group (12.7 ± 3.2) compared with the control group (6.2 ± 2.8; p < 0.001). Within-group analysis demonstrated statistically significant improvements from baseline in both groups (p < 0.001). The changes in BBS scores are described in **Figure 2**.

Table 3. Berg Balance Scale (BBS)

Assessment	Group A (n = 23)	Group B (n = 23)	p-value
Pre-treatment	34.8 ± 4.6	35.2 ± 4.9	**0.779**
Post-treatment	47.5 ± 4.1	41.4 ± 4.6	**<0.001**
Mean Change	**12.7 ± 3.2**	**6.2 ± 2.8**	**<0.001**

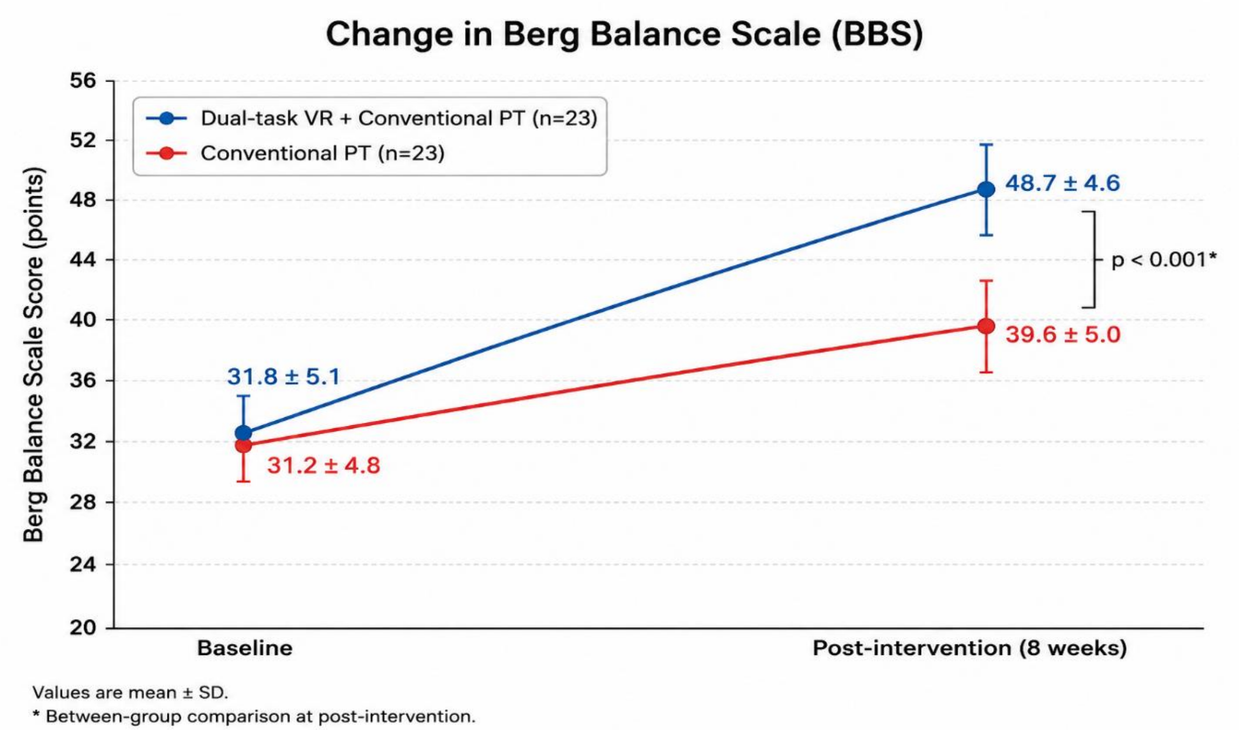

Figure 2. *Change in Berg Balance Scale (BBS) Scores*

Gait Performance

Timed Up and Go Test (TUG)

Both groups demonstrated significant improvements in functional mobility following the intervention. There was no statistically significant difference in baseline Timed Up and Go (TUG) scores between the experimental and control groups (23.4 ± 4.3 vs. 23.0 ± 4.2 seconds; p = 0.752), indicating comparable mobility status before treatment. Following the intervention, the experimental group demonstrated significantly lower TUG completion times than the control group (15.9 ± 3.2 vs. 19.6 ± 3.7 seconds; p = 0.001). The mean improvement in TUG performance was significantly greater in the experimental group (7.5 ± 2.2 seconds) than in the control group (3.4 ± 1.9 seconds; p < 0.001). Within-group analysis demonstrated statistically significant improvements in both groups (p < 0.001). The changes in TUG are illustrated in **Figure 3**.

Table 4. Timed Up and Go Test

Assessment	Group A (n = 23)	Group B (n = 23)	p-value
Pre-treatment (sec)	23.4 ± 4.3	23.0 ± 4.2	0.752
Post-treatment (sec)	15.9 ± 3.2	19.6 ± 3.7	0.001
Mean Improvement (sec)	7.5 ± 2.2	3.4 ± 1.9	<0.001

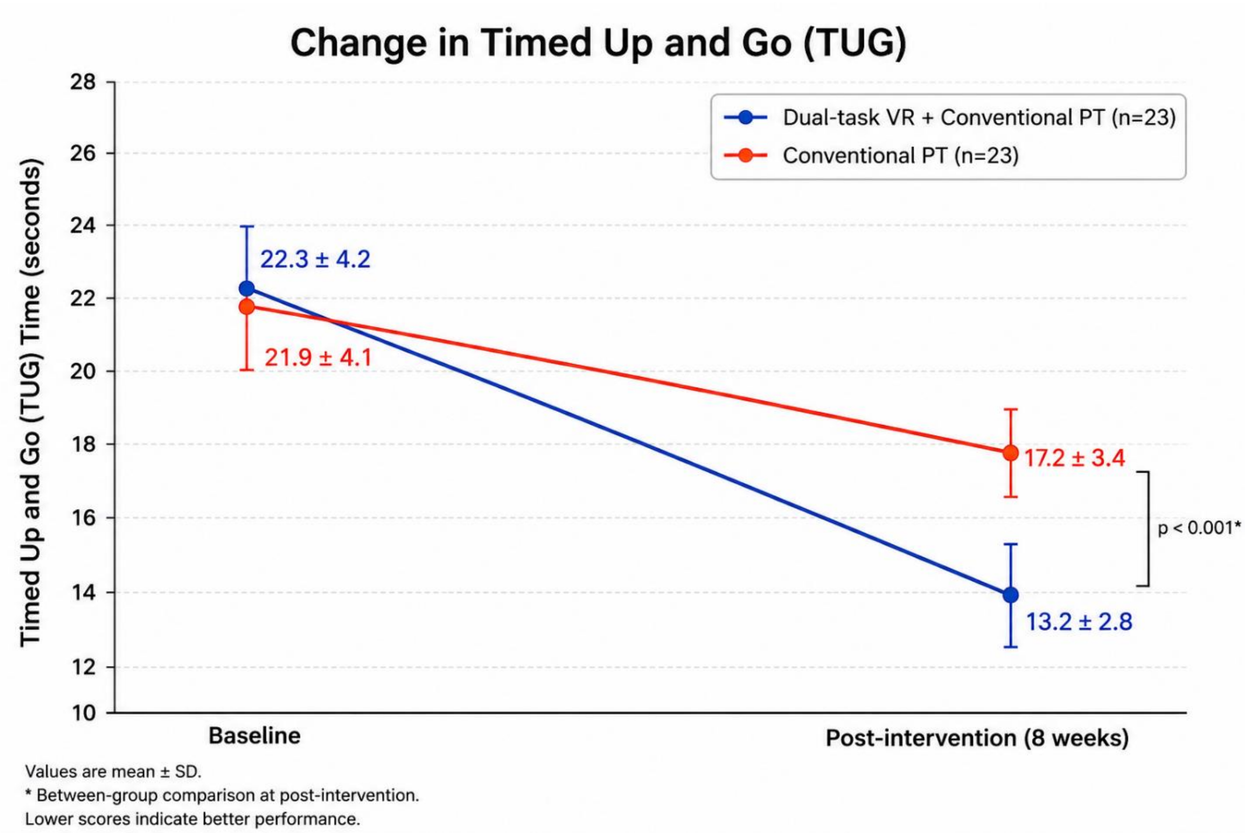

Figure 3. *Change in Timed Up and Go (TUG) Performance*

10-Meter Walk Test

Both groups demonstrated significant improvements in walking speed following the intervention. There was no statistically significant difference in baseline 10-Meter Walk Test (10MWT) performance between the experimental and control groups (0.64 ± 0.10 m/s vs. 0.65 ± 0.11 m/s; p = 0.748), indicating comparable gait performance at baseline. Following the intervention, participants in the experimental group achieved significantly higher walking speeds than those in the control group (0.92 ± 0.12 m/s vs. 0.79 ± 0.11 m/s; p < 0.001). The mean improvement in walking speed was significantly greater in the experimental group (0.28 ± 0.07 m/s) than in the control group (0.14 ± 0.06 m/s; p < 0.001). Within-group analysis demonstrated statistically significant improvements in walking speed in both groups (p < 0.001). The changes in 10 Meter Walk Test are illustrated in **Figure 4**.

Table 5. 10-Meter Walk Test

Assessment	Group A (n = 23)	Group B (n = 23)	p-value
Pre-treatment (m/s)	0.64 ± 0.10	0.65 ± 0.11	0.748
Post-treatment (m/s)	0.92 ± 0.12	0.79 ± 0.11	<0.001
Mean Improvement (m/s)	0.28 ± 0.07	0.14 ± 0.06	<0.001

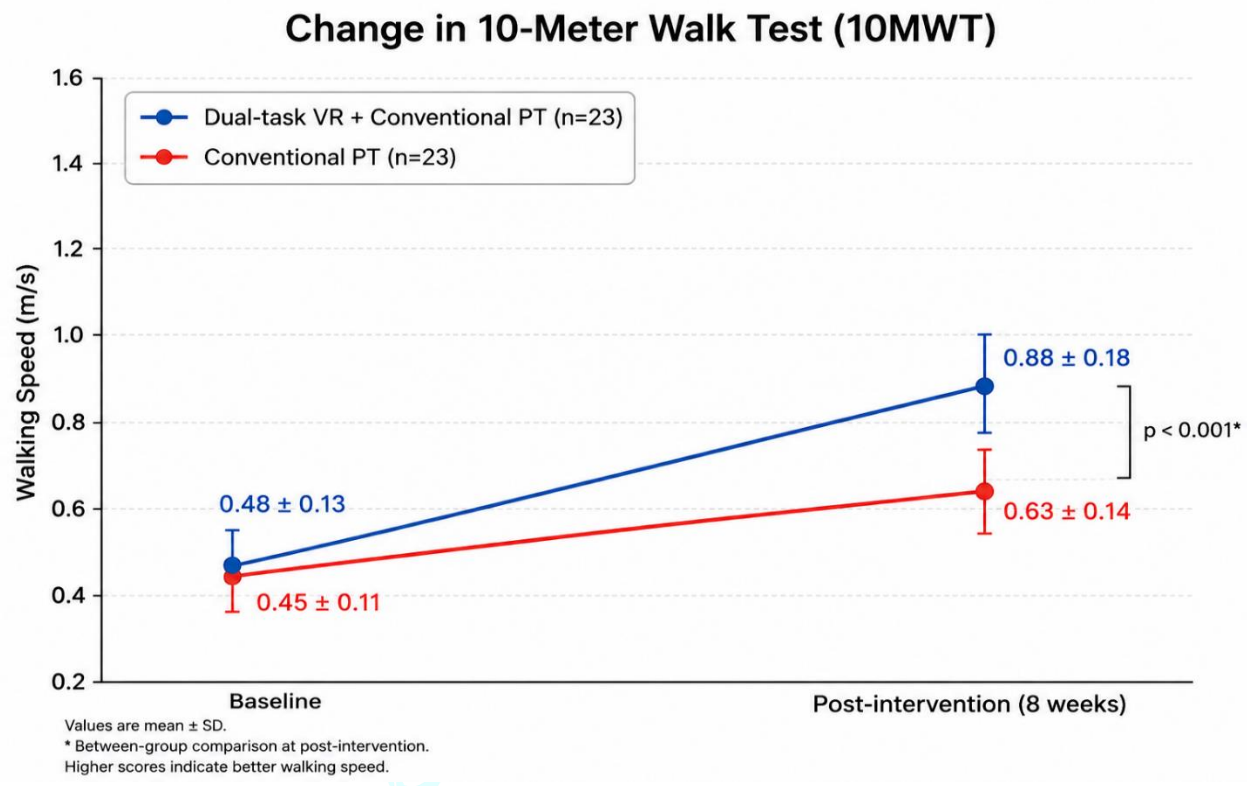

Figure 4. *Change in 10-Meter Walk Test (10MWT) Performance*

Cognitive Function

Montreal Cognitive Assessment (MoCA)

Both groups demonstrated significant improvements in cognitive function following the intervention. Baseline Montreal Cognitive Assessment (MoCA) scores were comparable between the experimental and control groups (20.5 ± 2.7 vs. 20.8 ± 2.6; p = 0.701). Following the intervention, the experimental group achieved significantly higher post-treatment MoCA scores than the control group (26.0 ± 2.2 vs. 22.8 ± 2.4; p < 0.001). The mean improvement in cognitive function was significantly greater in the experimental group (5.5 ± 1.8 points) than in the control group (2.0 ± 1.4 points; p < 0.001). Within-group analysis demonstrated statistically significant improvements in cognitive function in both groups (p < 0.001). The changes in MoCA are illustrated in **Figure 5**.

Table 6. Montreal Cognitive Assessment

Assessment	Group A (n = 23)	Group B (n = 23)	p-value
Pre-treatment	20.5 ± 2.7	20.8 ± 2.6	0.701
Post-treatment	26.0 ± 2.2	22.8 ± 2.4	<0.001
Mean Improvement	5.5 ± 1.8	2.0 ± 1.4	<0.001

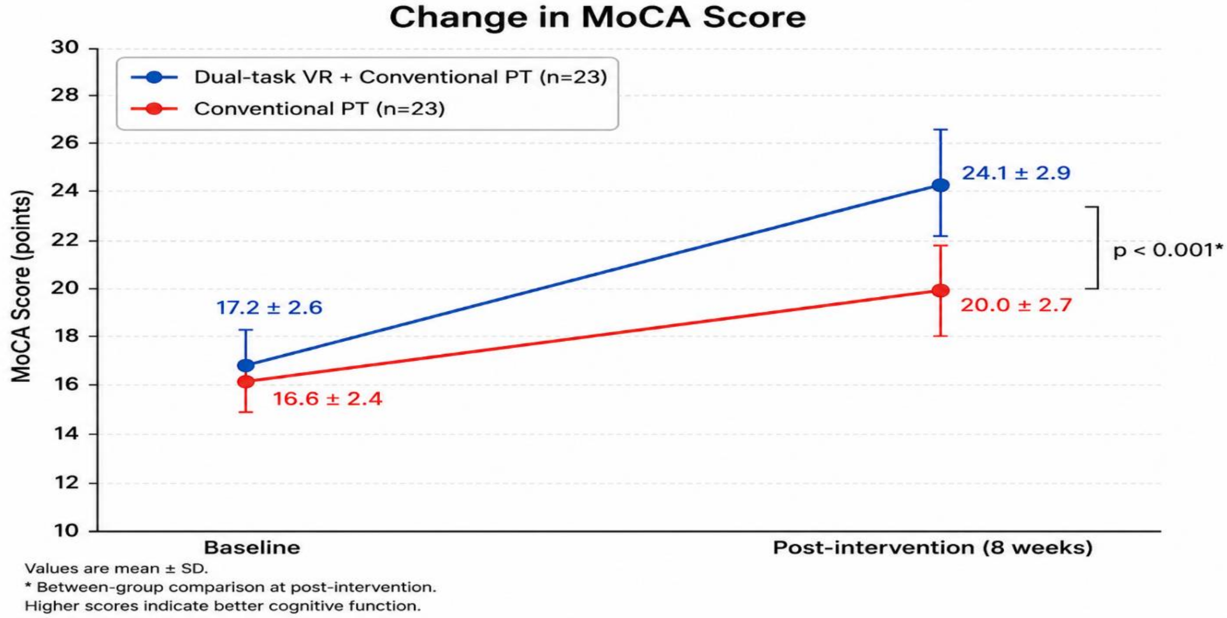

Figure 5. *Change in Montreal Cognitive Assessment (MoCA) Scores*

ANCOVA Analysis

Analysis of covariance (ANCOVA), controlling baseline scores, demonstrated statistically significant between-group differences across all outcome measures following the intervention. The experimental group showed significantly greater improvements in balance (Berg Balance Scale: $F = 23.47$, $p < 0.001$, partial $\eta^2 = 0.353$), functional mobility (Timed Up and Go: $F = 17.83$, $p < 0.001$, partial $\eta^2 = 0.293$), gait speed (10-Meter Walk Test: $F = 19.21$, $p < 0.001$, partial $\eta^2 = 0.309$), and cognitive function (MoCA: $F = 20.46$, $p < 0.001$, partial $\eta^2 = 0.322$) compared with the control group after adjusting for baseline values. The partial eta-squared values indicate large effect sizes for all measured outcomes, suggesting a substantial treatment effect of dual-task virtual reality training.

Table 7. ANCOVA Comparing Post-Intervention Outcomes Between Groups (Adjusted for Baseline Scores)

Outcome	F-value	p-value	Partial η^2
Berg Balance Scale	23.47	<0.001	0.353
Timed Up and Go	17.83	<0.001	0.293
10-Meter Walk Test	19.21	<0.001	0.309
MoCA	20.46	<0.001	0.322

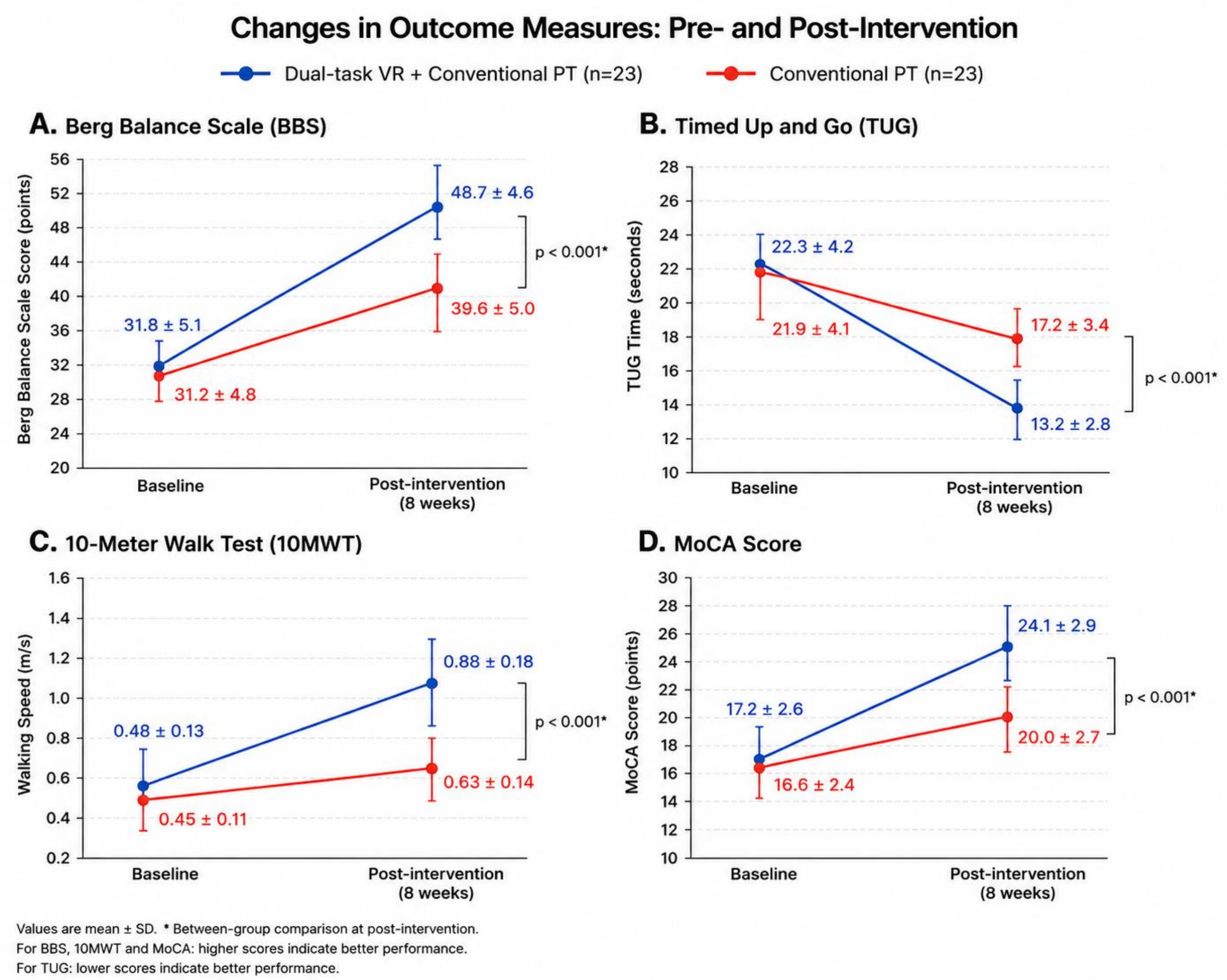

Figure 6. *Changes in Outcome Measures Following Intervention (Combined Figure)*

Discussion

The present study evaluated the effectiveness of dual-task virtual reality (VR) training combined with conventional physiotherapy in improving balance, functional mobility, gait performance, and cognitive function among individuals with strokes. Overall, the findings suggest that participants receiving dual-task VR training experienced greater improvements in balance, functional mobility, gait speed, and cognitive performance than those receiving conventional physiotherapy alone. These findings support the growing body of evidence indicating that integrating motor and cognitive tasks within an immersive virtual environment can enhance post-stroke rehabilitation outcomes beyond those achieved with conventional therapy alone (7, 10).

One of the principal findings of the present study was the greater improvement in Berg Balance Scale scores among participants who received dual-task VR training. Balance impairment is one of the most common residual deficits after stroke and significantly contributes to falls, reduced independence, and impaired quality of life (2, 3). The enhanced improvement observed in the intervention group may be attributed to the ability of virtual reality systems to provide repetitive, task-oriented practice with immediate visual and auditory feedback. Such enriched environments encourage active participation, increase motivation, and promote motor learning through continuous error correction. Additionally, the simultaneous performance of cognitive and motor tasks likely enhanced postural control by improving attentional allocation and executive processing during balance activities (6, 7).

These findings are consistent with previous investigations demonstrating the beneficial effects of virtual reality-based rehabilitation on postural stability after stroke. Laver et al. reported that virtual reality interventions improve balance and functional performance by providing engaging, repetitive, and goal-oriented exercises (10). More recent systematic reviews by Yang et al., Navas-Otero et al., and Cardile et al. also demonstrated that dual-task and VR-based rehabilitation strategies produce greater improvements in balance than conventional physiotherapy alone, particularly among individuals recovering from stroke (8, 11, 14). The findings of the present study therefore reinforce the role of VR-based dual-task training as an effective adjunct to conventional rehabilitation.

The present study also demonstrated greater improvements in Timed Up and Go performance among participants receiving dual-task VR training. Functional mobility requires efficient integration of balance, lower limb strength, coordination, and cognitive processing, particularly during transitional movements such as standing, turning, and walking. Improvements in functional mobility following VR-based rehabilitation may result from repeated practice of dynamic activities that closely resemble real-life functional tasks. The incorporation of cognitive challenges during movement may further improve attentional flexibility and movement automaticity, enabling participants to perform functional tasks more efficiently (5, 6).

Previous studies have similarly reported significant improvements in functional mobility following virtual reality interventions. Meta-analyses have demonstrated that dual-task training and VR-assisted rehabilitation significantly improve walking ability, mobility, and dynamic balance compared with conventional rehabilitation (8, 11). These findings highlight the potential of technology-assisted rehabilitation for improving functional independence after stroke.

Another important finding of the present study was the greater improvement in gait speed measured using the 10-Meter Walk Test. Restoration of walking ability remains one of the primary goals of stroke rehabilitation because gait speed is strongly associated with community participation, independence, and quality of life (2, 3). The observed improvements may reflect enhanced motor coordination, improved weight shifting, increased lower limb muscle activation, and better integration of sensory feedback during walking. The interactive nature of VR training encourages repetitive stepping practice while simultaneously challenging cognitive functions, which may facilitate neural adaptation and improve locomotor performance (7, 10, 13).

These findings agree with previous literature demonstrating that task-specific VR interventions significantly improve gait speed following stroke. Recent systematic reviews have concluded that combining virtual reality with conventional physiotherapy enhances walking performance more effectively than conventional therapy alone (9, 14). The repetitive practice, increased motivation, and enriched sensory feedback provided by virtual environments are believed to facilitate neuroplastic changes that contribute to improvements in gait performance (10, 13).

In addition to motor recovery, the present study found greater improvements in cognitive function as measured by the Montreal Cognitive Assessment following dual-task VR training. Cognitive deficits involving attention, executive function, processing speed, and working memory frequently coexist with motor impairments after stroke and often limit successful rehabilitation (4). The simultaneous engagement of cognitive and motor processes during VR exercises may stimulate multiple cortical networks responsible for executive functioning while reinforcing motor learning. Such integrated rehabilitation approaches are increasingly recognized as effective strategies for addressing both physical and cognitive impairments simultaneously (5, 12).

These findings are supported by emerging evidence suggesting that dual-task rehabilitation enhances cognitive recovery after stroke. Studies have demonstrated improvements in executive function, divided attention, and cognitive flexibility following combined cognitive-motor training (7, 14). Virtual reality provides realistic environments that require continuous problem-solving, decision-making, and attentional control, thereby promoting cognitive engagement alongside physical rehabilitation (10, 13).

Several physiological mechanisms may explain the observed benefits of dual-task VR training. Repetitive, task-oriented practice is known to promote experience-dependent neuroplasticity by strengthening synaptic connections and facilitating cortical reorganization within motor and cognitive networks. Simultaneous activation of sensory, visual, vestibular, and proprioceptive pathways may enhance multisensory integration, improving postural stability and motor coordination. Furthermore, the motivational and interactive characteristics of virtual reality increase patient engagement and adherence, potentially resulting in greater training intensity and improved rehabilitation outcomes (13, 14). The addition of cognitive tasks may also improve dual-task performance by enhancing executive control and attentional resource allocation, both of which are essential for safe community ambulation (6, 12).

The findings of the present study have important clinical implications. Incorporating dual-task VR training into conventional stroke rehabilitation programs may provide clinicians with an effective strategy for simultaneously addressing motor and cognitive impairments. The engaging nature of VR-based interventions may improve patient motivation, increase therapy adherence, and encourage higher repetitions during rehabilitation sessions (9, 13).

The large partial eta-squared values observed across all outcomes indicate that dual-task VR training produced clinically meaningful treatment effects, supporting previous meta-analytic findings that immersive rehabilitation enhances both motor and cognitive recovery.

Overall, the present study contributes to the growing evidence supporting the integration of virtual reality into stroke rehabilitation. By simultaneously targeting motor and cognitive impairments through dual-task training, VR-based rehabilitation has the potential to improve functional recovery and optimize rehabilitation outcomes in individuals recovering from stroke (7, 8).

Strengths

This study has several methodological strengths. The randomized controlled trial design enhanced the internal validity of the findings by minimizing selection bias through random allocation, while assessor blinding helped reduce measurement bias. The use of standardized and validated outcome measures to evaluate balance, gait, and cognitive function ensured reliable and clinically relevant assessment of rehabilitation outcomes. Furthermore, the simultaneous evaluation of motor and cognitive domains provided a comprehensive understanding of functional recovery following stroke and allowed the clinical effectiveness of dual-task virtual reality training to be assessed from multiple perspectives. To our knowledge, this is among the few randomized controlled trials evaluating the combined effects of dual-task virtual reality training on balance, gait, and cognition within a single rehabilitation protocol.

Limitations

Despite these strengths, several limitations should be acknowledged. The study was conducted at a single rehabilitation center with a relatively modest sample size, which may limit the generalizability of the findings. The intervention period was limited to the treatment duration, and no long-term follow-up was performed to determine whether the observed improvements were sustained over time. In addition, important patient-centered outcomes, including quality of life, community participation, activities of daily living, and long-term fall incidence, were not evaluated. Variability in stroke characteristics, such as lesion location, severity, and time since stroke onset, may also have influenced individual responses to the intervention but was not explored in subgroup analyses. Future multicenter randomized controlled trials with larger sample sizes, standardized dual-task virtual reality protocols, extended intervention periods, and longer follow-up are recommended to confirm these findings, evaluate their long-term sustainability, and establish the clinical and cost-effectiveness of dual-task virtual reality rehabilitation for individuals with stroke.

Conclusion

This randomized controlled trial evaluated the effectiveness of dual-task virtual reality (VR) training combined with conventional physiotherapy in individuals with stroke. The study found that participants receiving dual-task VR training demonstrated greater improvements in balance, gait performance, and cognitive function than those receiving conventional physiotherapy alone. These findings suggest that integrating cognitive and motor training within an interactive virtual environment may enhance functional recovery by simultaneously improving postural control, walking ability, attention, and executive function. Incorporating dual-task VR training into conventional stroke rehabilitation may therefore represent a valuable strategy for addressing the complex motor and cognitive impairments commonly experienced after stroke. Nevertheless, larger multicenter randomized controlled trials with standardized intervention protocols and longer follow-up periods are warranted to confirm these findings, evaluate their long-term sustainability, and strengthen the evidence supporting the routine clinical implementation of dual-task VR rehabilitation.

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