

Effect of virtual reality-based functional treadmill training on gait parameters in young ischaemic stroke survivors: a randomised controlled trial

original paper

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HANAN HOSNY M. BATTESHA¹ , AMIR N. WADEE^{2,3} , SAMAH HOSNEY NAGIB^{4,5} ,
MARK MONIR SEDDIK⁶ 

¹ Physical Therapy Department, Faculty of Applied Medical Sciences, Al-Zaytoonah University of Jordan, Amman, Jordan

² Basic Sciences Department, Faculty of Physical Therapy, Cairo University, Cairo, Egypt

³ Basic Sciences Department, Faculty of Physical Therapy, Sinai University, Qantara Branch, Egypt

⁴ Department of Physical Therapy, Faculty of Applied Medical Sciences, Al-Zaytoonah University of Jordan, Amman, Jordan

⁵ Department of Physical Therapy for Surgery and Burn, Faculty of Physical Therapy, Cairo University, Cairo, Egypt

⁶ Department of Physical Therapy for Internal Medicine and Geriatrics, Badr University in Assiut (BUA), Assiut, Egypt

ABSTRACT

Purpose. Ischaemic stroke is a major cause of long-term disability and is commonly associated with gait impairments that reduce functional independence and quality of life. Conventional rehabilitation often provides limited continued gait training after discharge. Virtual reality (VR)-based functional treadmill training offers immersive, task-specific practice and can enhance recovery. Objective: To investigate the effect of VR-based functional treadmill training on spatiotemporal gait parameters in young individuals with ischaemic stroke.

Methods. A randomised controlled trial was conducted on 28 patients with subacute ischaemic stroke (aged 35–45 years), randomly assigned to two equal groups. The study group received VR-based treadmill training plus conventional therapy, while the control group received conventional rehabilitation including treadmill training. The intervention lasted 6 weeks. Gait velocity was the primary outcome, and other spatiotemporal gait parameters were secondary outcomes. Assessments were performed pre- and post-intervention using the Tekscan HR Walkway system.

Results. The study group showed greater improvement in gait velocity than the control group (1.36 ± 0.27 vs. 1.28 ± 0.20 m/s, $p = 0.004$, $\eta^2 = 0.26$). Step time decreased significantly (484.47 ± 18.05 vs. 544.47 ± 34.97 ms, $p < 0.001$, $\eta^2 = 0.47$), as did swing time (0.36 ± 0.01 vs. 0.37 ± 0.02 s, $p = 0.013$, $\eta^2 = 0.20$). Stride length increased significantly (1.37 ± 0.07 vs. 1.35 ± 0.08 m, $p = 0.029$, $\eta^2 = 0.16$). No significant difference was found in stride time ($p = 0.377$).

Conclusions. VR-based treadmill training improved several spatiotemporal gait parameters compared with conventional therapy in young stroke survivors. The findings should be interpreted cautiously due to the small sample size and the short study duration.

Key words: ischaemic stroke, virtual reality-based functional treadmill training, spatiotemporal kinematic gait analysis

Introduction

A stroke is a vascular injury that can affect both men and women, with evidence indicating gender differences in incidence, risk factors, and prognosis. Ischaemic stroke represents one of the leading causes of morbidity and mortality worldwide and is the most common stroke subtype, accounting for approximately 85–90% of all stroke cases due to obstruction of cerebral blood flow [1, 2]. Stroke in young adults (≤ 45 years) has been

reported to represent a notable proportion of ischaemic stroke cases, with a prevalence of approximately 12.99% and a mean age of 37.56 ± 7.52 years, with a higher incidence in males [3].

Stroke occurrence in early and middle adulthood is associated with substantial morbidity. Its increasing incidence has been linked to the rising prevalence of modifiable risk factors such as hypertension, hypercholesterolemia, obesity, diabetes mellitus, smoking, and cardiovascular disease, in addition to non-mod-

Correspondence address: Hanan Hosny M. Battesha, Physical Therapy Department, Faculty of Applied Medical Sciences, University of Jordan, Airport Street (Queen Alia Airport Road), Street 594, Amman 11733, Al-Zaytoonah, Jordan, e-mail: h.hosny@zuj.edu.jo; <https://orcid.org/0000-0003-3242-4978>

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ifiable or less modifiable factors including migraine, pregnancy-related conditions, illicit drug use, oral contraceptive use, and hypercoagulable states. The underlying mechanisms of stroke in younger populations are often heterogeneous and include cervical artery dissection, cardioembolic events, vasculitis, connective tissue disorders, patent foramen ovale, and cerebral venous thrombosis [4]. Although younger patients demonstrate relatively favourable functional outcomes, many still present with mild neurological impairment or minimal disability as assessed by standardised clinical scales [5].

Post-stroke motor impairments are highly prevalent, with gait disturbances reported in approximately 80% of survivors [6]. These gait impairments are typically characterised by reduced walking speed, decreased stride length, and temporal-spatial asymmetry resulting from muscle weakness, altered muscle tone, and postural instability. Such deficits negatively affect functional independence and increase the risk of falls, thereby reducing quality of life [7]. Biomechanically, stroke patients often demonstrate prolonged stance time on the non-paretic limb, reduced stance time and range of motion on the paretic limb, and disrupted inter-limb coordination during the gait cycle. These alterations are accompanied by changes in lower limb kinematics and muscle activation patterns, particularly in the tibialis anterior, gastrocnemius, and hamstring muscles [8, 9].

Conventional treadmill training improves walking speed through repetitive stepping practice; however, it does not fully address the adaptive demands of real-world walking. Functional ambulation requires continuous adjustment to environmental challenges such as obstacle negotiation, directional changes, and dual-task activities [10]. However, conventional rehabilitation settings often lack the resources and space required to safely simulate these real-life conditions.

To address these limitations, VR-based treadmill training has been developed, providing task-specific gait training with real-time visual feedback in an immersive and interactive environment [11]. By incorporating augmented reality features such as obstacle avoidance, variable-speed walking, and balance challenges, VR-based training can enhance motor learning and promote neuroplasticity [12]. Unlike conventional treadmill training, VR-based interventions improve the transfer of acquired gait skills to real-world walking performance, thereby enhancing rehabilitation outcomes. Evidence suggests that VR-based rehabilitation improves gait and motor function after stroke by

enabling task-specific, repetitive training in an enriched, interactive environment that enhances neuroplasticity and promotes greater engagement than conventional therapy [13, 14].

Despite growing evidence supporting the use of VR-based interventions in gait rehabilitation, the existing literature shows considerable variability in intervention protocols, outcome measures, and assessment tools. Furthermore, limited studies have incorporated objective sensor-based gait analysis systems to quantify treatment effects with high precision. This lack of standardisation and integration of advanced assessment technologies highlights a gap in the current literature, particularly in evaluating the effectiveness of VR-based treadmill training on specific spatiotemporal gait parameters in stroke survivors. Therefore, we hypothesised that patients receiving VR-based functional treadmill training would demonstrate significantly greater improvements in gait performance, particularly gait velocity, compared to those receiving conventional physical therapy.

Although sensor-based gait analysis systems such as Tekscan and GAITRite are increasingly used in rehabilitation research, variability in measurement protocols, data processing methods, and outcome interpretation remains a challenge, highlighting the need for standardised, validated assessment approaches in stroke rehabilitation studies.

Material and methods

Design of the study

This study was a randomised controlled prospective study conducted at a single physical therapy centre to examine the effects of VR-based gait training in patients with sub-acute stroke. The study was assessor-blinded, with outcome assessors blinded to participants' group allocation to minimise the risk of measurement bias.

Sample size

The sample size was calculated based on a pilot study with five participants per group. The required sample size was determined using G*Power software (version 3.1.9.2; Franz Faul, University of Kiel, Germany). A total sample size of 28 participants (14 per group) was required, assuming an alpha level of 0.05, a statistical power of 80% and an effect size of 0.47 derived from the pilot study.

Participants

The twenty-eight patients included in the study were first-ever stroke cases, confirmed by neuroimaging that ruled out any previous silent infarctions. All patients in the early stages of recovery under the guidance of a neurologist, underwent computed tomography or magnetic resonance imaging to confirm the diagnosis of stroke. The following were the inclusion criteria to the study: (1) age between 35 and 45 years, (2) the ability to stand upright for a minute, (3) the ability to walk on level surfaces without the use of mobility aids, (4) full consciousness and sufficient alertness to comprehend and follow instructions during evaluation and training, (5) demonstration of the Functional Ambulatory Category (FAC) score of at least 3, and (6) a Mini-Mental State Examination (MMSE) score above 23, indicating sufficient cognitive function to understand the study protocol, (7) a Timed Up and Go test score of less than 10, and (8) a Modified Ashworth Scale score between grade 1 and grade 1+. The following were the exclusion criteria: (1) chronic stroke (> 6 months after onset), (2) insufficient cardiovascular response to training, (3) fear of walking on the treadmill, (4) adverse changes in neurological and/or somatic

status, (5) significant co-occurring neurological, musculoskeletal, or cardiopulmonary conditions that affect gait, and (6) any other condition that the researchers deemed inappropriate.

Randomisation

Participants were randomly assigned in equal numbers to either group using a sealed, opaque envelope procedure. The allocation sequence was generated using a computer-based random number generator prior to participant enrolment to ensure true randomisation and allocation concealment. After initial screening and obtaining informed consent, participants were allocated accordingly. Both intervention protocols were conducted over a 6-week period under the supervision of skilled physiotherapists, with 14 participants in each group. A CONSORT flow diagram was used to illustrate participant enrolment, allocation, and follow-up (Figure 1). Due to the nature of the interventions, blinding of participants and treating therapists was not feasible. However, outcome assessment was performed by an independent assessor blinded to group allocation to minimise potential assessment bias.

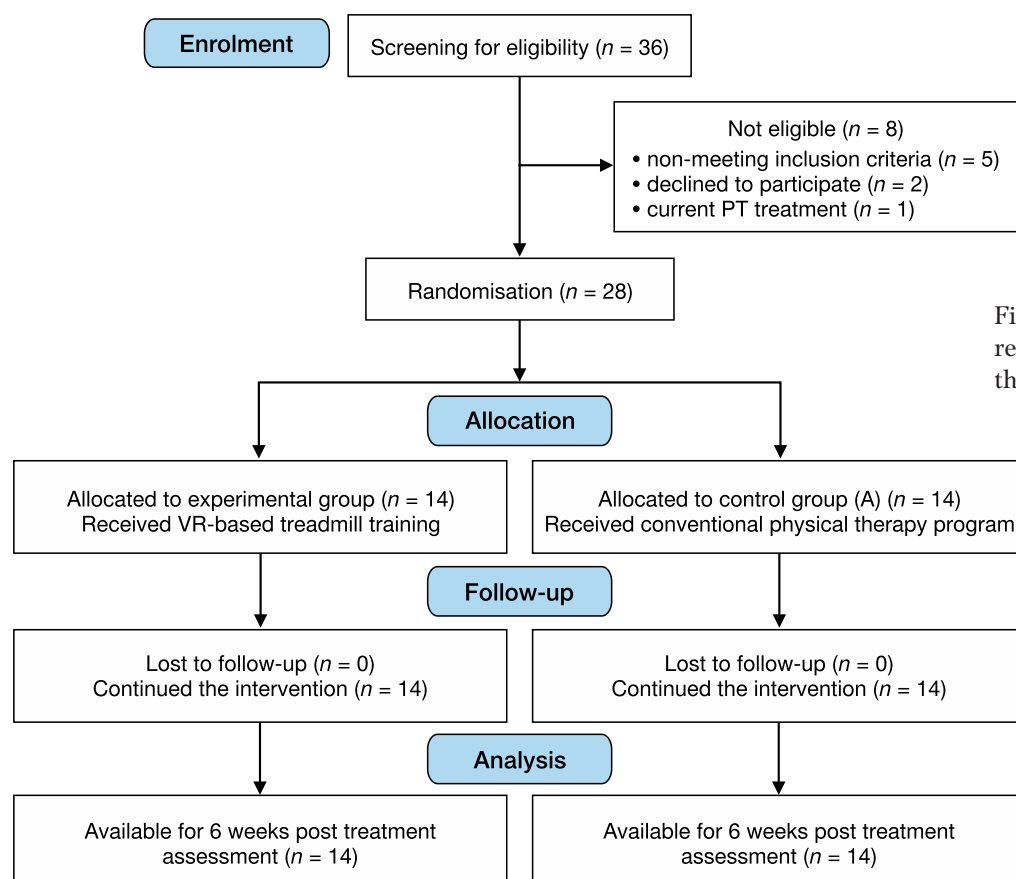


Figure 1. A flow chart of patients' recruitment and retention throughout the study

Outcome measures

Adherence was monitored by recording participants' attendance at each session, and all treatments were delivered using a standardised protocol by trained physiotherapists to ensure consistency and minimise therapist-related variability. Every evaluation was done both before and after the six-week treatment session.

The use of the Tekscan walkway Mat pressure measurement system highlights the importance of standardised protocols for data acquisition and interpretation when employing complex sensor technologies in clinical trials to ensure reliability and comparability of performance outcomes. The increasing use of sensor-based gait analysis systems in clinical research highlights the critical need for standardised, validated, and algorithm-driven assessment approaches. Variability in device accuracy, sensor placement, and underlying analytical algorithms affect the reliability and reproducibility of outcome measures. Therefore, the implementation of standardised frameworks for digital and decentralised assessment is essential to ensure the clinical validity of gait analysis in rehabilitation trials [15]. Walkway systems have demonstrated good agreement with reference systems across most gait parameters, supporting their validity in gait assessment [16]. The primary outcome was gait speed given the typical hemiparetic patterns characterised by decreased walking speed, while secondary outcomes included other gait parameters. The system included a digital mat positioned within a wooden walkway, with sensors embedded at a density of 4 sensors per cm² within the mat. A computer equipped with Tekscan Software (version 7) was utilised for evaluation and interpretation of the collected information. As the sensors recorded the spatiotemporal gait parameters of foot contact with the walkway, the software automatically computed gait speed (m/s), step time (s), stride time (s), swing time (s), and stride length (m). Before taking measurements, all participants were asked to walk three self-selected routes along the Tekscan walkway. This was done to allow the participant to become accustomed to the test process, whereupon three data sets were recorded and the average subsequently calculated.

Interventions

Participant compliance was monitored throughout the intervention period by recording session attendance and completion of the prescribed training sessions. Both groups received the same conventional physical therapy programme and equal total treatment dura-

tion and intensity. However, the study group received VR-based functional treadmill training, while the control group received traditional treadmill training without virtual reality. Thus, the only difference between groups was the presence of VR feedback during treadmill training. All interventions were delivered according to a standardised protocol by trained physiotherapists to reduce inter-therapist variability and ensure consistency of treatment delivery. Following baseline assessment after randomisation, participants in both groups underwent the intervention for six weeks, with training sessions conducted twice weekly for a total of twelve sessions. All gait outcome measures were assessed at baseline and at the end of the intervention period.

Participants in the study group received 30 min of VR-based functional treadmill training followed by 30 min of conventional physical therapy. The VR-based treadmill training incorporated real-time visual feedback and task-oriented gait challenges. Training was initiated at each participant's comfortable walking speed, with progressive adjustments in walking speed, step length, and task difficulty according to the participant's tolerance and performance.

Participants in the control group received 30 min of conventional physical therapy programme followed by 30 min of traditional treadmill training. The conventional programme focused on task-specific gait training, balance exercises, and walking activities on different surfaces, while the treadmill training involved repetitive linear walking at a controlled speed. Treadmill speed was set at each participant's self-selected comfortable walking speed, providing an individualised and safe speed for treadmill training.

VR-based functional treadmill training refers to treadmill walking combined with immersive VR feedback, where participants perform gait training while interacting with real-time visual scenarios that include functional tasks such as obstacle avoidance, speed modulation, and balance challenges, rather than simple repetitive treadmill walking. Feedback mechanisms are incorporated into VR-based gait rehabilitation systems to offer real-time assistance, either to correct erroneous motions or to motivate users. Real-time visual feedback incorporated into VR-based training has been shown to enhance motor control and attenuate neuromuscular fatigue by modulating interlimb neural activity and improving sensorimotor integration [17]. The system comprised a Woodway Desmo S treadmill, an HTC Vive Pro Eye HMD, and an Xsens IMU motion capture system. Custom software (Unity 2022.3) rendered real-time adaptive environments (city crossing,

park trail, supermarket). Training included speed adaptation, obstacle negotiation, incline simulation, and cognitive dual-tasks, adjusted in real time via a clinician's tablet. Standardised setup, calibration, and session protocols were followed, with all parameters logged for fidelity. In order to ensure that every session is as challenging as possible and pertinent to the patient's unique condition and progress, the current system takes into account a number of variables, including the patient's particular needs, the type of therapy to be administered, and the ability for therapists to modify the difficulty, duration, and type of activities in real time. Real-time visibility of their movements and progress gives patients a sense of success and motivates them to keep working hard. Furthermore, therapists have access to comprehensive patient progress data, enabling them to precisely modify the treatment plan. Step length, walking speed, and inclination at which the individual could maintain step symmetry were measured during the exercise. Step length and walking speed were only increased in each consecutive training session until the subject could complete the activity without experiencing gait rhythm, balance issues, or severe fatigue. The patient gradually removed the arm-rest while utilising a Bluetooth fingertip pulse oximeter to check their heart rate. Additionally, the activity intensity was gradually increased from 55% to 65% of the maximum heart rate. Exercise time, distance, and walking speed were displayed on the monitor. Patients engaged in breathing and circulatory exercises, active exercises, and balance exercises while sitting and standing prior to each treadmill training session.

Conventional physical therapy programme

The therapist advanced the patient's paretic leg while the patient stood on the paretic side to prevent the patient's pelvis from moving away from the bar. Patients can typically start with a parallel bar, perform walking exercises on various floor surfaces, including stairs and barriers, use a task-specific intensive walking training programme, perform resistance workouts in the upright position, use limb-load feedback, and complete a 30-minute walk on a traditional treadmill.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were presented as mean $\pm$ standard deviation. A mixed-design analy-

sis of variance (ANOVA) was used to examine the interaction effect between time (pre- and post-treatment) and group (study vs control). Post hoc pairwise comparisons were performed using Bonferroni correction to adjust for multiple comparisons of the spatiotemporal gait parameters. Effect sizes (Cohen's *d*) were calculated to determine the magnitude of between-group differences. Statistical significance was set at $p < 0.05$. All analyses were conducted on a complete-case (per-protocol) basis, as no missing data or dropouts were observed. Therefore, an intention-to-treat analysis was not required.

Results

No missing data were reported, and all participants completed the study without dropouts. Adherence to the intervention protocol was complete, with full attendance across all scheduled sessions. This high retention rate can be attributed to the relatively short intervention duration, close supervision, continuous monitoring, and the incorporation of VR-based training, which likely enhanced patient motivation, engagement, and compliance.

The primary outcome of this study was gait velocity (walking speed), while secondary outcomes included step time, stride time, swing time, and stride length.

There was a significant improvement in gait velocity in the study group compared to the control group at post-treatment ($p < 0.05$). Regarding secondary outcomes, significant between-group differences were observed in step time, swing time, and stride length ($p < 0.05$). However, stride time improved significantly in both groups, with no significant difference between groups at post-treatment.

General demographic data

Table 1 shows the baseline characteristics of the participants, with no significant differences observed between groups in age, height, weight, BMI, duration of illness, Timed Up and Go test, Mini-Mental State Examination scores, or sex distribution ($p > 0.05$).

Within-group comparisons

Both groups showed significant improvements in most gait spatiotemporal parameters following the intervention period. In the study group, significant reductions were observed in step time (pre: 605.73 ± 37.98 ms; post: 484.47 ± 18.05 ms, $p < 0.001$, $\eta^2 = 0.82$), stride time (pre: 1.15 ± 0.06 s; post: 1.04 ± 0.07 s, $p < 0.001$,

Table 1. Demographic data

Demographic data	Experimental group (mean $\pm$ SD)	Control group (mean $\pm$ SD)	ANOVA
Age (year)	39.9 $\pm$ 3.5	39.8 $\pm$ 3.9	0.915
Weight (kg)	69.5 $\pm$ 3.3	70.3 $\pm$ 4.1	0.440
Height (cm)	168.8 $\pm$ 7.5	167.1 $\pm$ 6.5	0.369
BMI (kg/m ²)	25.7 $\pm$ 1.7	25.4 $\pm$ 2.4	0.601
Functional ambulatory category	4.1 $\pm$ 0.8	4.1 $\pm$ 1.6	0.917
Duration of disease (month)	4.8 $\pm$ 0.5	4.9 $\pm$ 1.6	0.721
Timed up and go test (s)	8.7 $\pm$ 0.7	8.7 $\pm$ 1.9	0.927
Mini-mental state	25.2 $\pm$ 1.1	25.3 $\pm$ 1.7	0.784
HRmax (bpm)	175.2 $\pm$ 3.4	175.1 $\pm$ 3.5	0.910
Gender (n)	male: 10 female: 4	male: 10 female: 4	chi-square: 1

BMI – body mass index, HRmax – heart rate maximum, bpm – beats per minute

Table 2. Comparison of gait parameters between study and control groups pre- and post-intervention

Parameter	Study pre	Study post	Control pre	Control post	95% CI study (post)	95% CI control (post)	<i>p</i> (within study)	<i>p</i> (within control)	<i>p</i> (between pre)	<i>p</i> (between post)	Effect size (η^2 , partial eta squared)
Velocity (m/s)	1.07 $\pm$ 0.15	1.36 $\pm$ 0.27	1.08 $\pm$ 0.15	1.28 $\pm$ 0.20	1.21–1.51	1.17–1.39	0.001*	0.004*	0.532	0.004*	0.26
Step time (ms)	605.73 $\pm$ 37.98	484.47 $\pm$ 18.05	609.67 $\pm$ 36.86	544.47 $\pm$ 34.97	474.47–494.47	525.10–563.83	0.001*	0.001*	0.611	0.001*	0.47
Stride time (s)	1.15 $\pm$ 0.06	1.04 $\pm$ 0.07	1.17 $\pm$ 0.04	1.16 $\pm$ 0.04	1.00–1.08	1.13–1.18	0.001*	0.377	0.428	0.377	0.03
Swing time (s)	0.39 $\pm$ 0.02	0.36 $\pm$ 0.01	0.39 $\pm$ 0.02	0.37 $\pm$ 0.02	0.35–0.37	0.36–0.38	0.001*	0.013*	0.745	0.013*	0.20
Stride length (m)	1.22 $\pm$ 0.17	1.37 $\pm$ 0.07	1.23 $\pm$ 0.18	1.35 $\pm$ 0.08	1.33–1.41	1.30–1.39	0.003*	0.029*	0.689	0.029*	0.16

Values are presented as mean $\pm$ standard deviation (SD) with 95% confidence intervals (CI).

Effect size was calculated using eta squared (η^2) from ANOVA. Statistical significance was set at $p < 0.05$

$\eta^2 = 0.41$), and swing time (pre: 0.39 $\pm$ 0.02 s; post: 0.36 $\pm$ 0.01 s, $p < 0.001$, $\eta^2 = 0.46$). Significant improvements were also noted in gait velocity (pre: 1.07 $\pm$ 0.15 m/s; post: 1.36 $\pm$ 0.27 m/s, $p = 0.001$, $\eta^2 = 0.33$) and stride length (pre: 1.22 $\pm$ 0.17 m; post: 1.37 $\pm$ 0.07 m, $p = 0.003$, $\eta^2 = 0.27$). Similarly, the control group demonstrated significant improvements in step time, swing time, velocity, and stride length, although the magnitude of change was smaller compared to the study group. Stride time did not show statistically significant improvement ($p = 0.377$, $\eta^2 = 0.03$) (Table 2).

Between-group comparisons (post-intervention)

Post-intervention analysis revealed significant differences between groups in favour of the study group. Step time was significantly lower in the study group compared to the control group (484.47 $\pm$ 18.05 *vs.* 544.47 $\pm$ 34.97, $p < 0.001$, $\eta^2 = 0.47$). Similarly, significant between-group differences were observed in swing time ($p = 0.013$), gait velocity ($p = 0.004$), and stride length ($p = 0.029$), all favouring the study group.

Table 3. MANOVA for gait spatiotemporal parameters

Source	<i>F</i>	Sig.	Partial eta squared
Intercept	10080.20	0.000*	0.997
Group	21.09	0.000*	0.979

No significant difference in stride time was observed between groups post-intervention ($p = 0.377$).

Effect size interpretation

Effect size analysis indicated large effects for step time improvements in the study group and moderate-to-large effects for other gait parameters, supporting the clinical relevance of the observed change (Table 3).

Discussion

Although long-term outcomes after stroke are generally favourable, evidence suggests that persistent functional limitations still exist, highlighting the need for effective rehabilitation interventions. In line with

this, Pinter *et al.* [18] reported that, at a median follow-up of ten years, nearly 75% of stroke survivors achieved excellent functional outcomes, demonstrating independence in daily activities, although some residual symptoms and functional limitations persisted.

The present study demonstrated that VR-based functional treadmill training significantly improved gait spatiotemporal parameters, evidenced by reductions in step time, stride time, and swing time, and increases in stride length and gait velocity. These findings are consistent with previous studies reporting improvements in gait performance following VR-based treadmill training in stroke populations [19–22]. In particular, Wang *et al.* [21] found greater improvements in walking speed following VR-based treadmill training compared with conventional therapy, while Han *et al.* [22] reported significant benefits in functional mobility and gait performance.

It is important to note that variations across studies in terms of participant characteristics, intervention duration, and outcome measures influence the extent of observed improvements. For instance, differences in stroke stage, training intensity, and the type of gait assessment tools used contribute to variability in treatment responses, as highlighted in previous research on post-stroke gait variability, and should be considered when comparing results across studies [23].

Horstman *et al.* [24] demonstrated that functional recovery after stroke is closely associated with improvements in muscle properties essential for gait performance. Similarly, rehabilitation training has been shown to facilitate motor learning and neuromuscular adaptation by improving motor unit recruitment and interlimb coordination, thereby enhancing walking ability [25]. These mechanisms appear to underlie the improvements observed in the present study following task-specific, repetitive, and intensive VR-based gait training.

Furthermore, even in later phases after stroke, patients can achieve meaningful functional gains through intensive, task-oriented rehabilitation, although recovery potential tends to decrease over time [26, 27].

The effectiveness of VR-based treadmill training is further supported by its ability to simulate real-world walking tasks in a controlled environment. Unlike conventional rehabilitation, it enables repeated practice of functional activities such as obstacle negotiation, speed adaptation, and directional changes, which are essential for community ambulation [22].

From a neurophysiological perspective, multisensory integration of visual, vestibular, and proprioceptive inputs has been proposed to enhance motor adap-

tation and error correction [28]. Previous neuroimaging studies have also reported increased activation in motor-related cortical areas following VR-based training, reflecting enhanced motor learning and cortical reorganisation [29]. In addition, treadmill-based training has been associated with increased levels of neurotrophic factors such as brain-derived neurotrophic factor, which supports synaptic plasticity and motor recovery [30]. Repetitive and variable practice further contributes to improved neuromuscular control and more efficient gait patterns [31].

In younger stroke populations, VR-based rehabilitation is particularly relevant due to higher functional demands and rehabilitation goals. Its engaging and interactive nature enhances motivation and adherence, allowing for increased training intensity and repetition, which supports functional recovery [32, 33]. Compared with conventional rehabilitation, VR-based treadmill training has been associated with improved gait and functional outcomes [34].

Although most gait parameters showed significant improvement following VR-based treadmill training, stride time did not differ statistically significantly between groups. This finding suggests that temporal gait components are less responsive to short-term interventions and require longer training duration or more targeted task-specific approaches to achieve measurable adaptations. This result is consistent with previous findings indicating that temporal parameters, such as stride time, tend to show slower recovery than spatial gait parameters during post-stroke rehabilitation [35].

The observed improvements in gait parameters have important clinical implications, as increases in gait velocity and stride length, along with reductions in temporal gait parameters, are associated with improved functional mobility and greater independence in daily activities following stroke [36, 37].

The differential adaptation observed among gait parameters in the present study can be explained by underlying biomechanical and neurophysiological mechanisms. Although gait velocity, step time, and stride time are mathematically interrelated (with velocity being a function of step length and temporal parameters), this mathematical coupling does not necessarily yield uniform adaptations across all variables, as each parameter reflects distinct levels of locomotor control.

The significant improvement in gait velocity was primarily driven by increased stride length and reduced step time, reflecting enhanced spatiotemporal coordination, improved inter-limb synchronisation, and more efficient propulsion during the stance phase. Spatial

gait parameters are known to be more responsive to rehabilitation interventions following stroke, likely because they depend more on peripheral motor output and task-specific motor learning processes [38–40].

Importantly, although stride time is mathematically derived from step time and cadence, it represents a global descriptor of gait cycle timing that reflects overall rhythmic locomotor output. This parameter is characterised by lower variability and greater temporal stability, as it is regulated by higher-level supraspinal centres and spinal pattern-generating networks. These central timing mechanisms are less sensitive to short-term, task-specific adaptations than segmental gait components.

In contrast, step time reflects phase-specific temporal adjustments within the gait cycle and is therefore more sensitive to early changes in motor control and inter-limb coordination. Consequently, improvements in step time and stride length can significantly enhance gait velocity without necessarily producing a proportional change in stride time, particularly in the early stages of post-stroke recovery where adaptations are predominantly segmental rather than global.

Overall, these findings suggest that gait recovery following stroke occurs in a hierarchical manner, with spatial and phase-specific temporal parameters adapting earlier than global cycle timing measures. This pattern has been consistently reported in previous studies, which demonstrated that spatial gait parameters, such as stride length and walking speed, show greater and earlier responsiveness to rehabilitation than temporal parameters such as stride time [38–42].

These findings should be interpreted in light of several methodological limitations, including the relatively small sample size, short intervention duration, and absence of long-term follow-up, which affect the generalisability and sustainability of the observed improvements. Overall, the findings support the beneficial role of VR-based rehabilitation in improving gait performance following stroke, while also indicating that certain temporal gait parameters require longer or more intensive intervention strategies to achieve significant improvement.

Conclusions

VR-based functional treadmill training improved gait spatiotemporal parameters in patients with subacute stroke. The intervention was associated with enhanced gait performance, including increases in gait velocity and stride length and reductions in temporal gait parameters. These findings should be interpreted with caution in light of the study's limitations.

Further large-scale studies with longer follow-up periods are required to confirm these findings and establish long-term effectiveness.

Limitations

This study has several limitations that should be acknowledged. First, the relatively small sample size (14 participants per group) limits the generalisability of the findings. Second, the six-week intervention duration is insufficient to evaluate long-term effects or maximal functional recovery. Third, although outcome assessors were blinded to group allocation, participant and therapist blinding was not feasible due to the nature of the intervention, which introduces a potential risk of performance bias. In addition, despite the use of a standardised protocol, variability in therapist delivery cannot be completely excluded. Furthermore, the inclusion of multiple temporally related gait parameters without formal correction for multiple comparisons increases the risk of type I error; therefore, these findings should be interpreted with caution. Finally, the absence of long-term follow-up limits the ability to determine the sustainability of the observed improvements over time.

Recommendations

Future randomised controlled trials are recommended to include larger sample sizes to improve the generalisability of findings. Longer follow-up periods are also needed to evaluate the long-term sustainability of the observed improvements. In addition, incorporating functional and patient-reported outcome measures would provide a more comprehensive understanding of the clinical effectiveness of VR-based gait training. Further research comparing different rehabilitation protocols will help to optimise intervention strategies for post-stroke gait recovery.

Availability of data and materials

The data supporting the study's findings will be provided by the corresponding author upon reasonable request.

Ethical approval

The research related to human use complied with all the relevant national regulations and institutional policies and followed the tenets of the Declaration of Helsinki. The study protocol was filed as a clinical trial (NCT07200024) after being reviewed and approved by the Research Ethics Committee, Al Zaytoonah University, Jordan (approval No.: IRB#30/8/2024-2025).

Informed consent

Informed consent was obtained from all individuals included in this study. Before testing, each subject completed an informed consent form after all protocols were thoroughly described to them.

Conflict of interest

The authors state no conflict of interest.

Disclosure statement

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