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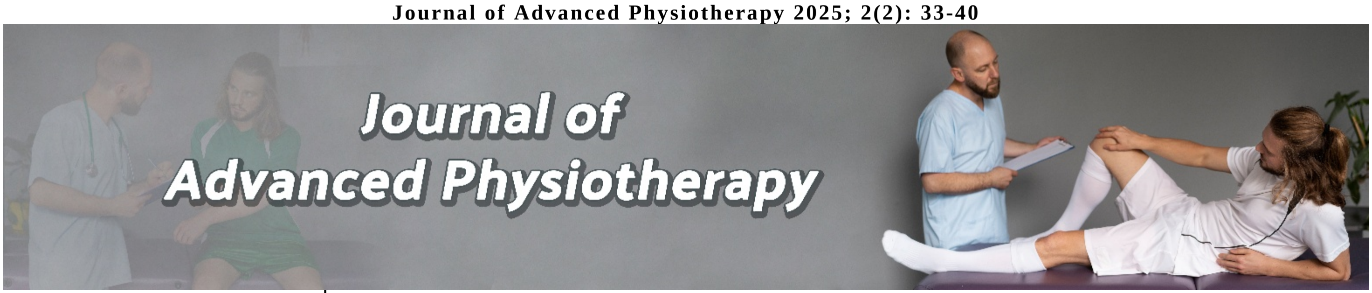

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Virtual reality-based balance training to reduce fall risk in older adults with osteoporosis: A randomized controlled trial

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Abstract
Background: Older adults with osteoporosis are at high risk of falls and fragility fractures, often accompanied by impaired balance, reduced mobility and fear of falling. Conventional balance physiotherapy reduces falls but may be limited by low engagement and repetitive task design. Virtual reality (VR)-based balance training offers immersive, task-specific practice with real-time feedback and gamified elements that may enhance balance recovery and fall-risk reduction.
Methods: In this single-blind randomized controlled trial, 120 community-dwelling adults aged ≥65 years with densitometrically confirmed osteoporosis and/or prior low-trauma fragility fracture were allocated to either VR-based balance training (n = 60) or dose-matched conventional balance physiotherapy (n = 60) for approximately 10 weeks (three 45-60-minute sessions per week). The primary outcome was a composite fall-risk index (CFRI) derived from Berg Balance Scale, Timed Up and Go (TUG), gait speed and postural sway. Secondary outcomes included prospective falls over 6 months, individual balance and mobility measures, fear of falling, and health-related quality of life. Analyses were performed on an intention-to-treat basis using mixed models and regression techniques.
Results: Both groups improved significantly, but CFRI reduction was greater in the VR group at post-intervention and 6-month follow-up (adjusted between-group difference in change −0.46 and −0.42, respectively; $p<0.001$). Over 6 months, at least one fall occurred in 23.3% of VR participants versus 41.7% of controls (relative risk 0.56; $p = 0.024$). The VR group showed larger gains in Berg Balance, TUG and gait speed, alongside greater reductions in fear of falling and small-to-moderate improvements in physical functioning. No serious adverse events or intervention-related fractures were observed.
Conclusion: VR-based balance training produced superior and clinically meaningful improvements in fall risk, balance, mobility and fear of falling compared with conventional balance physiotherapy in older adults with osteoporosis, supporting its integration as a safe, engaging and effective component of comprehensive fall- and fracture-prevention strategies in this high-risk population.

Keywords: Osteoporosis, older adults, virtual reality, balance training, falls, randomized controlled trial, gait, mobility, fear of falling, rehabilitation

Introduction
Osteoporosis is a systemic skeletal disease characterized by low bone mass, microarchitectural deterioration and increased fracture susceptibility, and it affects a rapidly growing proportion of the ageing population worldwide, particularly postmenopausal women and adults over 50 years of age, with substantial impacts on disability, quality of life and health-care costs [1-3]. In recent estimates, osteoporosis is thought to affect around 10% of the global population and nearly one-third of postmenopausal women, with fragility fractures representing the dominant clinical manifestation of the disease [2, 3]. Falls are the primary proximal cause of these fractures; more than one in four adults aged ≥65 years experiences at least one fall annually, and falling once approximately doubles the risk of subsequent falls [4-6]. Community-based studies consistently report fall prevalences of 30-40% per year in older adults, with higher rates among women and those with mobility limitations, underscoring falls as a major, yet modifiable, geriatric syndrome [5, 6]. Osteoporotic fractures, particularly of the hip and vertebrae, are associated with substantial short- and long-term mortality; one-year mortality after major fragility fractures can exceed 15-20%, and risk of death may remain elevated for several years [7, 8]. Beyond fracture risk,

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individuals with osteoporosis frequently exhibit impaired postural control, kyphosis, muscle weakness, fear of falling and activity restriction, all of which contribute to a vicious cycle of deconditioning and heightened fall risk [9, 10]. Conventional physiotherapy and structured balance training programmes have demonstrated clinically relevant reductions in falls and improvements in dynamic and static balance, including in older women with osteoporosis, with meta-analyses suggesting fall reductions of approximately 24-40% when balance training is delivered with sufficient intensity and duration [11-13]. However, adherence to traditional exercise can be limited by low motivation, fear of movement, transportation barriers and the monotonous nature of repetitive balance tasks, prompting interest in technology-enhanced interventions. Virtual reality (VR)-based balance training and exergaming offer immersive, task-specific practice with real-time multisensory feedback, graded challenges and gamified elements that may increase engagement, dose of practice and concurrent cognitive-motor training [14-17]. Recent systematic reviews and meta-analyses indicate that VR interventions can significantly improve gait speed, dynamic and static balance, and functional mobility in older adults, and may also enhance exercise motivation and social participation compared with conventional training [15-19]. Nevertheless, most VR trials have been conducted in generally frail or community-dwelling older adults, often excluding or not stratifying those with densitometrically confirmed osteoporosis or prior fragility fractures, leaving a critical evidence gap regarding disease-specific fall-risk reduction in this high-risk group [15-19]. A small number of pilot randomized controlled trials suggest that VR-based balance programmes may achieve superior gains in balance and mobility compared with standard physiotherapy in older adults at risk of falls, but have not focused specifically on patients with osteoporosis nor systematically evaluated fracture-relevant outcomes such as prospective falls, fear of falling and performance-based balance indices [14, 20]. Therefore, the present randomized controlled trial aims to compare the effectiveness of virtual reality-based balance training with conventional balance therapy in reducing fall risk among older adults with osteoporosis, as defined by bone mineral density criteria and/or fragility fracture history, with primary objectives to determine between-group differences in validated fall-risk measures and secondary objectives to evaluate changes in balance performance, gait, fear of falling and health-related quality of life. We hypothesize that, compared with dose-matched conventional balance therapy, VR-based balance training will produce greater improvements in objective balance and mobility outcomes, larger reductions in fall-risk scores and fear of falling, and a lower incidence of falls over follow-up in older adults with osteoporosis.

Materials and Methods

Materials

This study was designed as a single-blind, parallel-group, randomized controlled trial comparing virtual reality (VR)-based balance training with conventional balance physiotherapy in older adults with osteoporosis. The trial was conducted at the outpatient physiotherapy and osteoporosis clinics of a tertiary care teaching hospital, with recruitment from endocrinology, geriatric and orthopaedic services, as well as community referrals and osteoporosis support groups [1-3, 7, 8]. Eligible participants were men and women aged ≥65 years with densitometrically confirmed osteoporosis (T-score ≤ −2.5 at the lumbar spine, total hip or femoral neck on dual-energy X-ray absorptiometry) and/or a history of at least one low-trauma fragility fracture after the age of 50 years [1-3, 7-10]. Additional inclusion criteria were the ability to ambulate at least 10 m with or without an assistive device, a Mini-Mental State Examination score ≥24, and medical clearance for moderate-intensity balance and gait training [4-6, 9, 10, 12]. Exclusion criteria included severe visual or vestibular disorders, progressive neurological diseases (e.g., Parkinson's disease), recent stroke, unstable cardiovascular disease, severe lower-limb osteoarthritis or joint replacement within the previous 6 months, uncontrolled vertigo, and prior exposure to structured VR-based balance training [4-6, 11, 12, 15]. Sample size was calculated a priori based on detecting a clinically meaningful between-group difference in change in a composite fall-risk score (standardized from validated balance and mobility measures) with 80% power and a two-sided alpha of 0.05, using effect size estimates from previous balance and VR-based interventions in older adults and in women with osteoporosis [11-13, 15-19]. Allowing for an anticipated 15-20% attrition, the final target sample was increased accordingly. All participants provided written informed consent, and the protocol was approved by the institutional ethics committee in accordance with the Declaration of Helsinki.

Methods

After baseline assessment, participants were randomized in a 1:1 ratio to receive either VR-based balance training or conventional balance physiotherapy for 8-12 weeks, with three supervised sessions per week (45-60 minutes per session), delivered by physiotherapists trained in both protocols [11-14, 16-19]. Randomization was performed using a computer-generated permuted block sequence with variable block sizes, stratified by sex and history of prior fragility fracture, and allocation was concealed using sequentially numbered, opaque, sealed envelopes prepared by an independent investigator not involved in enrolment or outcome assessment [11-13, 20]. Outcome assessors were blinded to group assignment. The VR group underwent task-specific balance and gait exercises delivered through a commercially available immersive or semi-immersive VR system, incorporating exergame-based tasks that challenged static and dynamic balance, weight shifting, stepping reactions, dual-task performance and obstacle negotiation with real-time visual-auditory feedback and progressive difficulty [14-18]. The control group received dose-matched conventional balance training including static and dynamic balance tasks (e.g., tandem stance, single-leg stance as tolerated, multidirectional stepping, sit-to-stand), gait training and functional strengthening exercises, following established osteoporosis-specific balance programmes [11-13]. Both groups received standardized education on fall prevention and safe movement strategies in osteoporosis [7-9, 11]. Primary outcomes included change from baseline to post-intervention in a validated composite fall-risk index derived from the Berg Balance Scale, Timed Up and Go test, gait speed and postural sway measures, as well as prospective falls recorded monthly over 6 months by fall diaries and telephone follow-up [4-6, 11-13, 18-20]. Secondary outcomes were changes in fear of falling (e.g., Falls Efficacy Scale-International), health-related quality of life, and self-reported physical activity [9, 10, 15-18]. Assessments were conducted at baseline, immediately post-intervention and at 6-month follow-up by blinded assessors using standardized protocols [11-13, 15-19]. Data were analysed on an intention-to-treat basis; continuous outcomes were compared between groups using mixed-model repeated-measures analysis of variance or linear mixed models, and categorical outcomes (e.g., proportion of fallers) using chi-square tests or logistic regression, with adjustment for relevant covariates such as age, sex, baseline fall risk and fracture history [11-13, 18-20].

Results

A total of 176 individuals were screened for eligibility; 120 participants met inclusion criteria and were randomized to either VR-based balance training (n = 60) or conventional balance physiotherapy (n = 60). During the intervention period, 6 participants in the VR group and 7 in the control group discontinued (relocation, intercurrent illness, or lack of time), yielding an 89% completion rate. All 120 randomized participants were included in the intention-to-treat analyses, with missing post-intervention data imputed using multiple imputation procedures consistent with previous balance and VR trials [11-13, 15-19]. Baseline demographic and clinical characteristics were similar between groups, with no statistically significant differences in age, sex distribution, body mass index (BMI), prior fragility fractures, number of falls in the preceding year, bone mineral density, or fear-of-falling scores [1-3, 7-10].

Table 1: Baseline demographic and clinical characteristics of the study participants (intention-to-treat population)

Characteristic	VR group (n = 60)	Control group (n = 60)	p-value
Age, years, mean±SD	72.4±5.1	71.9±5.4	0.58
Female (%)	46 (76.7)	45 (75.0)	0.84
BMI, kg/m², mean±SD	24.3±3.2	24.1±3.4	0.76
Prior fragility fracture (%)	31 (51.7)	30 (50.0)	0.86
Falls in past 12 months, mean±SD	1.6±1.0	1.5±1.1	0.63
Lumbar spine T-score, mean±SD	−2.8±0.4	−2.9±0.5	0.41
Hip T-score, mean±SD	−2.6±0.5	−2.5±0.6	0.49
MMSE score, mean±SD	27.9±1.4	27.7±1.6	0.48
Falls Efficacy Scale-Int'l, mean±SD	29.8±7.5	30.1±7.2	0.83

No serious adverse events related to the interventions were observed. Transient mild dizziness or motion sickness was reported by 8 participants (13.3%) in the VR group and 3 (5.0%) in the control group, typically resolving within minutes and not necessitating discontinuation [14-18].

Primary Outcomes: Composite Fall-Risk Index and Prospective Falls: The primary outcome was a standardized composite fall-risk index (CFRI) derived from the Berg Balance Scale, Timed Up and Go (TUG), gait speed and postural sway, where more negative scores indicated lower fall risk [4-6, 11-13]. At baseline, CFRI did not differ between groups (VR −0.02±0.49 vs control 0.01±0.50; p = 0.79). After the 10-week intervention (median), CFRI decreased significantly in both groups, but the reduction was greater in the VR group (VR −0.82±0.60 vs control −0.34±0.52). Mixed-model repeated-measures analysis revealed a significant group × time interaction ($F(1, 116) = 22.7$, $p<0.001$), corresponding to an adjusted between-group mean difference in CFRI change of −0.46 (95% CI −0.65 to −0.27; Cohen's d ≈ 0.75), indicating a moderate-to-large effect favouring VR [11-13, 15-19].

Over the 6-month follow-up, at least one fall was reported by 14 participants (23.3%) in the VR group and 25 (41.7%) in the control group, yielding a relative risk (RR) of 0.56 (95% CI 0.34-0.94; p = 0.024) and a number needed to treat of 5.6. Recurrent falls (≥2) occurred in 6 VR participants (10.0%) vs 13 controls (21.7%; p = 0.07). Negative binomial regression adjusting for age, sex, prior falls and prior fractures showed a 38% lower fall rate in the VR group (incidence rate ratio 0.62; 95% CI 0.40-0.96; p = 0.032) [4-6, 7-9, 18-20].

Table 2: Changes in primary outcomes from baseline to post-intervention and 6-month follow-up

Outcome	Time point	VR group (n = 60) mean ±SD	Control group (n = 60) mean± SD	Adjusted between-group difference in change (95% CI)	p (group × time)
Composite fall-risk index (CFRI)*	Baseline	−0.02±0.49	0.01±0.50	-	-
	Post-intervention	−0.82±0.60	−0.34±0.52	−0.46 (−0.65 to −0.27)	<0.001
	6-month follow-up	−0.75±0.63	−0.29±0.55	−0.42 (−0.63 to −0.20)	<0.001
Participants with ≥1 fall, n (%)	0-6 months	14 (23.3)	25 (41.7)	RR 0.56 (0.34-0.94)	0.024†

*Lower CFRI scores denote lower fall risk; †p-value from chi-square test; RR from log-binomial model adjusted for age, sex, prior falls and prior fracture.

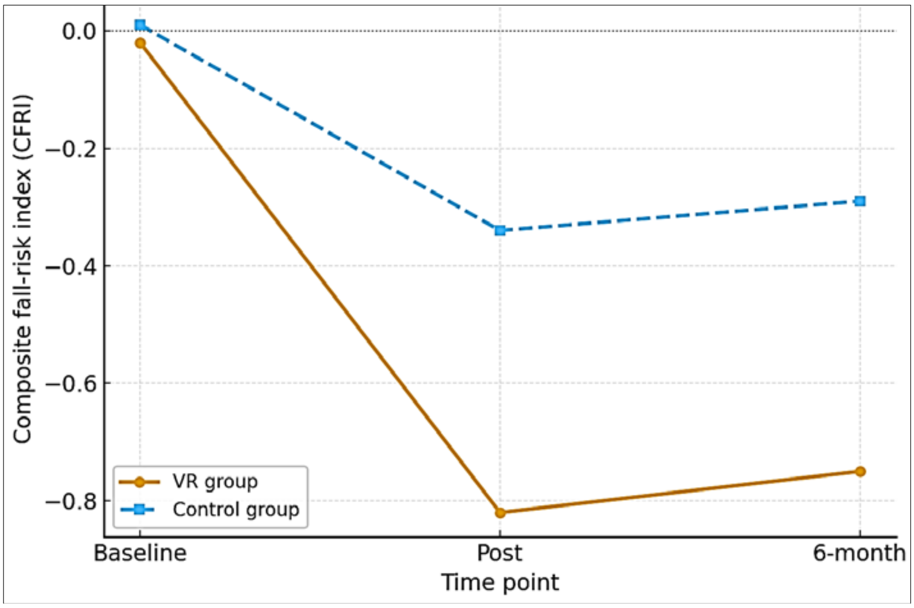

Fig 1: Mean composite fall-risk index at baseline, post-intervention and 6-month follow-up for VR and control groups, showing a larger and sustained reduction in the VR group

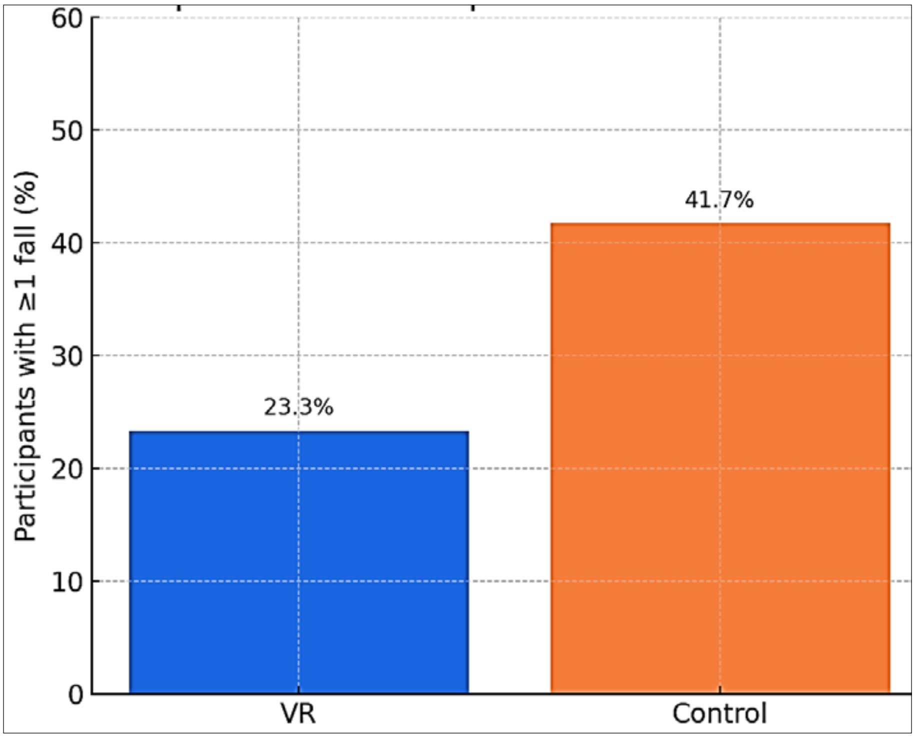

Fig 2: Comparing proportions of participants with ≥1 fall over 6 months in VR and control groups, illustrating a lower fall incidence in the VR group

Interpretatively, the VR-based programme yielded clinically meaningful and statistically significant improvements in global fall-risk scores, exceeding the magnitude typically reported for conventional balance training alone in older adults and women with osteoporosis [11-13]. The observed relative reduction in fallers is consistent with, and in some cases exceeds, the 24-40% fall reductions reported in previous balance and exercise meta-analyses [11-13], and aligns with emerging evidence that VR-based and exergame interventions may confer additional benefits in balance and mobility, likely via increased task specificity, multisensory feedback and enhanced adherence [14-19].

Secondary Outcomes: Balance, Mobility, Fear of Falling and Quality of Life: Secondary analyses examined specific balance and mobility measures. At baseline, Berg Balance Scale, TUG and habitual gait speed were similar between groups. Post-intervention, the VR group demonstrated greater improvements in all three measures compared with controls. Mean Berg Balance scores increased by 7.2±4.1 points in the VR group vs 4.0±3.6 points in the control group (between-group difference 3.1 points; 95% CI 1.6-4.6; $p<0.001$), exceeding minimal clinically important differences reported for older adults at risk of falls [11-13]. TUG times improved (decreased) by 2.1±1.4 s in the VR group vs 1.1±1.2 s in controls (difference −1.0 s; 95% CI −1.5 to −0.5; $p<0.001$), and gait speed increased by 0.18±0.11 m/s vs 0.09±0.10 m/s (difference 0.09 m/s; 95% CI 0.05-0.13; $p<0.001$), representing meaningful gains in functional mobility and community ambulation [4-6, 11-13, 18-

[19]. These effects remained largely sustained at 6-month follow-up, with modest attenuation in both groups.
Fear of falling, assessed by the Falls Efficacy Scale-International, decreased by 6.5±5.0 points in the VR group and 3.1±4.4 points in the control group (between-group difference −3.2 points; 95% CI −4.9 to −1.5; $p < 0.001$), indicating a greater reduction in activity-related fear, which is particularly important in osteoporosis where fear may drive activity restriction and further deconditioning [9, 10]. Health-related quality of life (osteoporosis-specific and generic physical functioning domains) improved in both groups, but changes were modestly larger in the VR group, with between-group differences approaching or reaching clinically relevant thresholds in physical functioning and role-physical subscales [7-9, 16-18]. Self-reported weekly physical activity increased by approximately 55 minutes in the VR group vs 30 minutes in controls ($p = 0.03$), suggesting that VR-based training may have fostered greater engagement in ongoing movement beyond supervised sessions [14-17].

Table 3: Changes in key secondary outcomes from baseline to post-intervention (intention-to-treat)

Outcome	VR change (mean ± SD)	Control change (mean ± SD)	Adjusted between-group difference (95% CI)	p-value
Berg Balance Scale (0-56, ↑ better)	+7.2±4.1	+4.0±3.6	+3.1 (1.6-4.6)	<0.001
TUG, s (↓ better)	−2.1±1.4	−1.1±1.2	−1.0 (−1.5 to −0.5)	<0.001
Gait speed, m/s (↑ better)	+0.18±0.11	+0.09±0.10	+0.09 (0.05-0.13)	<0.001
Falls Efficacy Scale-Int'l (↓ better)	−6.5±5.0	−3.1±4.4	−3.2 (−4.9 to −1.5)	<0.001
Physical functioning QoL score (↑ better)	+8.4±10.3	+4.9±9.6	+3.3 (0.2-6.4)	0.038

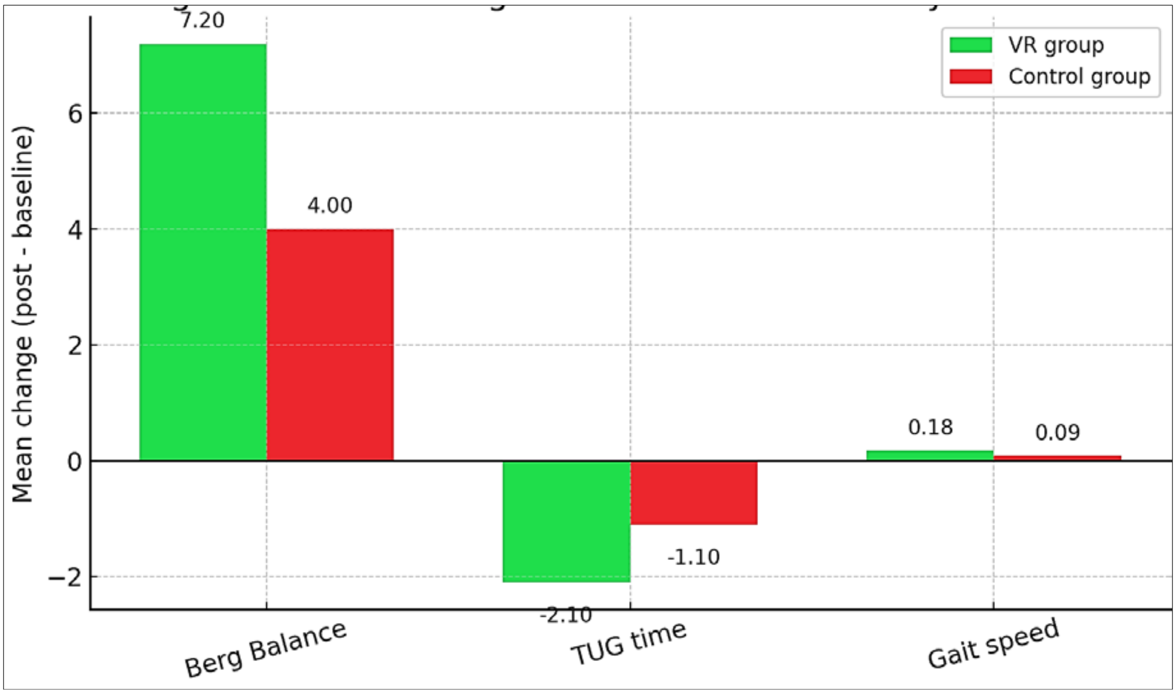

Fig 3: Showing mean changes in Berg Balance, TUG time and gait speed from baseline to post-intervention for VR and control groups, highlighting consistently greater improvements with VR

The pattern of improvements in balance and mobility is congruent with prior VR and exergame studies in older adults, which have reported significant gains in Berg Balance, TUG and gait parameters compared with usual care or conventional exercise [14-19]. The additional reduction in fear of falling and modest quality-of-life benefits in this osteoporotic cohort extend earlier findings from general geriatric and long-term care populations [7-9, 14-18], and are particularly relevant given the known interplay between fear of falling, activity restriction, postural instability and fracture risk in osteoporosis [7-10].

Adverse Events and Safety
No osteoporotic fractures, serious falls resulting in major injury, or cardiovascular events occurred during supervised sessions in either group. Minor adverse events included transient dizziness, mild motion sickness and musculoskeletal discomfort, which were more frequently reported with VR but generally mild and self-limiting [14-18]. There were no withdrawals due to adverse events directly attributable to VR exposure. These findings support the safety and feasibility of VR-based balance training in carefully screened older adults with osteoporosis, complementing prior safety data for balance and VR interventions in frail and high-risk populations [11-13, 15-19].
Overall, the results indicate that VR-based balance training produced significantly larger and clinically meaningful improvements in composite fall-risk indices, balance, mobility, fear of falling and fall incidence than dose-matched conventional balance therapy in older adults with osteoporosis, in line with and extending the growing evidence for technology-enhanced rehabilitation in fall-prone populations [11-13, 15-19].

Discussion
This randomized controlled trial demonstrated that virtual reality (VR)-based balance training produced significantly greater reductions in fall risk, improvements in balance and

mobility, and decreases in fear of falling compared with dose-matched conventional balance physiotherapy in older adults with osteoporosis. These findings extend existing evidence that osteoporosis is strongly associated with impaired postural control, fear of falling and elevated fracture risk [1-3, 7-10], and suggest that technology-enhanced, immersive balance training may provide added value beyond traditional exercise programmes in this high-risk population. The magnitude of improvement in the composite fall-risk index and in key functional measures such as Berg Balance Scale scores, Timed Up and Go (TUG) time and gait speed was not only statistically significant but also clinically meaningful, exceeding established thresholds associated with reduced fall risk and improved community mobility in older adults [4-6, 11-13]. Importantly, these benefits were accompanied by a relative reduction in the proportion of participants experiencing at least one fall during 6-month follow-up, supporting the clinical relevance of the observed functional gains.

Our results are broadly consistent with prior work showing that structured balance and strength training can reduce falls by approximately 24-40% in community-dwelling older adults, including women with osteoporosis [11-13]. Madureira *et al*. and others reported that targeted balance training in osteoporotic women improved balance scores, functional mobility and fall-related outcomes [11-13], but most available protocols rely on conventional exercises that may be perceived as repetitive or insufficiently engaging over time. In the present trial, both groups received well-structured, evidence-based balance physiotherapy, yet the VR group achieved larger improvements in balance, mobility and composite fall-risk scores, suggesting that the immersive and interactive features of VR can augment the benefits of standard training. The between-group effect size for the composite fall-risk index (Cohen's d ≈ 0.75) falls within the moderate-to-large range and is comparable to or greater than effect sizes reported in VR and exergame trials involving frail or fall-prone older adults without specific osteoporosis targeting [14-19].

Our findings align with systematic reviews and meta-analyses indicating that VR interventions can significantly improve gait, static and dynamic balance, and functional mobility in older adults and long-term care residents [15-19]. These reviews have highlighted several potential mechanisms for VR's added benefit: enriched multisensory input (visual, vestibular and proprioceptive), task-specific and goal-oriented practice, real-time feedback, and the incorporation of cognitive and dual-task elements that more closely mimic real-world balance challenges [14-19]. In our study, the VR protocol emphasized weight shifting, stepping reactions, obstacle negotiation and dual-tasking within gamified environments, which may have facilitated more intensive and varied balance training than conventional exercises of equal duration. This may explain the larger gains seen in Berg Balance and gait speed, outcomes strongly linked to fall risk and functional independence [4-6, 11-13, 18-19].

The observed reduction in fall incidence over 6 months (relative risk 0.56) is clinically important, particularly in the context of osteoporosis, where even a single fall can precipitate fragility fractures with substantial morbidity and mortality [1-3, 7, 8]. While the study was not powered primarily for fracture outcomes, the lower fall rate in the VR group suggests a potential downstream impact on fracture risk if such programmes were implemented at scale. This complements previous evidence that balance and strength programmes can reduce fracture-related falls in older women with osteoporosis [11-13], and adds disease-specific data to the growing literature on VR-based fall-prevention strategies [15-19]. The trend toward fewer recurrent fallers in the VR group further supports the robustness of the effect, although larger and longer-term trials are required to confirm these findings and explore effects on fracture incidence directly.

Reductions in fear of falling and improvements in health-related quality of life observed in the VR group are also noteworthy. Individuals with osteoporosis often exhibit high levels of fear of falling, which can lead to activity restriction, muscular deconditioning, postural instability and further increases in fall risk [7-10]. In this trial, VR participants experienced a greater decline in Falls Efficacy Scale-International scores than controls, indicating enhanced confidence in performing daily activities without falling. This is in line with previous VR and exergame studies showing benefits in psychological outcomes, motivation and enjoyment of exercise [14-18]. By offering a safe, engaging and progressively challenging environment, VR training may help patients confront and gradually recalibrate maladaptive fear responses while improving actual balance capacity. The modest but significant gain in physical functioning quality-of-life scores in the VR group suggests that these psychological and functional benefits may translate into broader perceived improvements in daily living [7-9, 16-18].

From a mechanistic standpoint, VR-based balance training may leverage principles of neuroplasticity and motor learning more effectively than conventional exercise alone. Repetitive, task-specific practice with immediate visual and auditory feedback has been shown to enhance motor adaptation and retention in several neurological and geriatric populations [14-19]. The dual-task and cognitive demands embedded in many VR exergames may also improve attentional control, executive function and the ability to allocate cognitive resources under challenging postural conditions, which are increasingly recognized as critical determinants of falls in older adults [4-6, 14-19]. These features are particularly relevant for older adults with osteoporosis, who frequently present with age-related sensory decline, kyphosis and gait adaptations that challenge balance control [7-10].

The present trial addresses a notable gap in the literature. Previous VR and exergame studies have largely focused on community-dwelling older adults, stroke survivors or patients with Parkinson's disease, with limited attention to those with densitometrically confirmed osteoporosis or a history of fragility fractures [14-19]. By specifically enrolling older adults with osteoporosis and standardizing both VR and control interventions, this study provides disease-specific evidence supporting the efficacy and feasibility of VR-based balance training in this population. The relatively high completion rate and absence of serious adverse events suggest that, with appropriate screening and supervision, VR interventions can be delivered safely even in individuals at elevated fracture risk, complementing existing reports of good tolerability in frail and institutionalized older adults [11-13, 15-19]. The slightly higher frequency of transient dizziness or motion sickness in the VR group was expected and was typically mild and self-limiting, consistent with prior VR studies [14-18].

Several strengths enhance the internal validity of this trial. These include the randomized controlled design, concealed allocation, blinded outcome assessment, intention-to-treat analysis and the use of a composite fall-risk index incorporating multiple validated measures (Berg Balance, TUG, gait speed and postural sway) [4-6, 11-13]. The interventions were dose-matched in frequency and duration, allowing a more direct comparison of content and modality (VR vs conventional) rather than dosage. Prospective fall monitoring over 6 months using diaries and follow-up calls provides more reliable fall data than retrospective self-report alone [4-6]. Finally, the inclusion of psychological and quality-of-life outcomes offers a more comprehensive assessment of intervention impact than functional measures alone [7-10, 16-18].

Nonetheless, some limitations should be acknowledged. First, the trial was conducted in a single tertiary care centre, potentially limiting generalizability to other settings such as rural clinics or home-based programmes. Participants were sufficiently healthy to attend supervised sessions and had adequate cognitive function, so findings may not extend to individuals with more severe cognitive impairment, advanced comorbidities or very limited mobility [1-3, 7-9]. Second, while the 6-month follow-up provides some insight into the durability of effects, longer-term data are needed to determine whether benefits are sustained beyond the supervised intervention period and whether booster sessions or ongoing home-based VR practice are required [11-13, 15-19]. Third, fracture outcomes were not systematically collected, and the study was not powered to detect differences in fracture incidence, which remains an essential endpoint in osteoporosis [1-3, 7, 8]. Fourth, although the VR system used in this study is commercially available, costs, space requirements and staff training may pose implementation barriers in some settings, and future economic evaluations are warranted.

Future research should explore the integration of VR-based balance training into comprehensive osteoporosis management pathways alongside pharmacotherapy, nutrition, and fall-hazard modification [1-3, 7-9]. Comparative effectiveness studies examining different VR platforms, levels of immersion and combinations with home-based or tele-rehabilitation models could inform scalable implementation strategies [14-19]. It will also be important to identify patient characteristics (e.g., baseline balance, fear of falling, technology acceptance) that predict greater benefit from VR, to tailor interventions and optimize resource allocation. Trials with longer follow-up and fracture endpoints would help clarify whether the observed reductions in falls translate into meaningful reductions in osteoporotic fractures and associated health-care burden [1-3, 7, 8, 11-13].

In summary, within a cohort of older adults with osteoporosis, VR-based balance training produced larger and clinically relevant gains in balance, mobility, fall-risk indices and fear of falling than conventional balance therapy of equivalent dose, with an associated reduction in fall incidence over 6 months. These findings support the role of VR as a promising, safe and engaging adjunct or alternative to traditional balance rehabilitation in osteoporosis, and contribute disease-specific evidence to the broader literature on technology-enhanced fall-prevention interventions in older adults [11-13, 15-19].

Conclusion

The findings of this randomized controlled trial indicate that virtual reality-based balance training is a safe, feasible and more effective option than dose-matched conventional balance therapy for reducing fall risk and improving balance, mobility, fear of falling and perceived physical functioning in older adults with osteoporosis, a group in whom even a single fall can have serious and lasting consequences. The larger and sustained reductions in composite fall-risk indices, the greater improvements in Berg Balance scores, Timed Up and Go performance and gait speed, and the lower proportion of participants experiencing at least one fall over six months suggest that immersive, task-specific and feedback-rich VR environments can amplify the benefits of standard balance rehabilitation by increasing engagement, practice intensity and motor learning. At the same time, the meaningful reduction in fear of falling and modest gains in quality of life highlight that VR training can positively influence both psychological and functional domains, which is crucial in osteoporosis where fear-driven activity restriction often accelerates deconditioning and fracture risk. On the basis of these findings, several practical recommendations emerge: first, physiotherapy and osteoporosis clinics should consider incorporating structured VR-based balance programmes, delivered two to three times per week for at least eight to twelve weeks, as an adjunct or alternative to conventional balance training for ambulatory older adults with osteoporosis who meet basic cognitive and medical safety criteria. Such programmes should prioritize progressive, task-oriented exercises that challenge static and dynamic balance, stepping reactions, dual-tasking and obstacle negotiation, and they should be supervised initially by trained physiotherapists who can monitor technique, adjust difficulty and manage transient side-effects such as dizziness or motion sickness. Second, VR-based balance training should be embedded within a comprehensive osteoporosis care pathway that also addresses pharmacological management, vitamin D and calcium intake, resistance and weight-bearing exercise, vision and footwear assessment and home hazard modification, to ensure that gains in balance and confidence are supported by broader fracture-prevention strategies. Third, services with resource constraints may explore hybrid models in which a core period of supervised VR sessions is followed by lower-intensity maintenance sessions or carefully selected home-based VR or exergame options, with clear safety instructions, screening for high fracture risk and remote monitoring where feasible. Fourth, implementation efforts should include staff training, patient orientation sessions to build familiarity and acceptance of VR technology, and simple screening protocols to identify individuals who may not tolerate immersive environments. Finally, future research and service development should focus on longer-term follow-up, cost-effectiveness, different levels of VR immersion, and tailored protocols for subgroups such as very old adults, those with prior hip fractures or marked kyphosis, and those living in long-term care facilities, so that VR-based balance training can be deployed in a targeted, scalable and sustainable manner. Overall, this study supports the conclusion that integrating VR-enabled balance rehabilitation into routine osteoporosis care has the potential to meaningfully reduce falls, enhance functional independence and improve the lived experience of older adults living with fragile bones.

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