

Virtual Reality-Based Interventions for Fall Prevention in Older and High Fall-Risk Adults: A Systematic Review of Randomized Controlled Trials

Yaşlı ve Düşme Riski Yüksek Yetişkinlerde Düşmeyi Önlemede Sanal Gerçeklik Temelli Müdahaleler: Randomize Kontrollü Çalışmaların Sistematiik Derlemesi

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ABSTRACT

Objective: This systematic review evaluated the effects of virtual reality (VR)-based interventions on prospectively recorded fall outcomes in older adults and high fall-risk adult populations.

Materials and Methods: PubMed and Scopus were systematically searched for randomized controlled trials published between January 2015 and December 2025. Eligible studies included adults aged ≥ 60 years or populations explicitly characterised as high fall-risk (e.g., neurological conditions associated with increased fall risk), a VR-based or interactive virtual training intervention targeting fall prevention, balance, gait, or mobility, a comparator group, and prospective reporting of fall outcomes (e.g., fall incidence, fall rate, proportion of fallers, or incidence rate ratio). Six randomized and RCT-derived reports met the inclusion criteria. Due to heterogeneity in intervention modalities, fall outcome definitions, and follow-up durations, meta-analysis was not performed; instead, a structured narrative synthesis was conducted. Risk of bias was assessed using the Cochrane RoB 2 tool.

Results: Six randomized and RCT-derived reports were included, with sample sizes ranging from 26 to 302 participants and follow-up periods ranging from 3 to 12 months where available. The included interventions were mainly based on non-immersive VR or interactive virtual training systems integrated with gait, balance, or cognitive-motor tasks. Fall outcomes were reported using heterogeneous metrics, including fall incidence, fall rate, fall frequency, fall counts, and incidence rate ratios. The most favourable signals were observed in treadmill-based gait training combined with non-immersive VR and cognitive-motor challenges. No study was judged as having high risk of bias; one trial demonstrated overall low risk, while the remaining trials presented some concerns.

Conclusion: VR-based interventions, particularly non-immersive systems integrating cognitive-motor demands within structured gait training, may contribute to fall prevention in older and high fall-risk adults. However, the small number of trials, heterogeneity in intervention designs and fall outcome reporting, and relatively short follow-up periods warrant cautious interpretation. Future pragmatic randomized trials should use standardized fall definitions and prospectively recorded fall incidence or fall-event outcomes as primary endpoints.

Keywords: Geriatrics, Accidental Falls, Virtual Reality, Aged, Rehabilitation

ÖZ

Amaç: Bu sistematiik derlemede, sanal gerçeklik (VR) temelli müdahalelerin yaşlı bireylerde ve düşme riski yüksek yetişkin popülasyonlarda prospektif olarak kaydedilmiş düşme sonuçları üzerindeki etkileri değerlendirilmiştir.

Gereç ve Yöntem: Ocak 2015 ile Aralık 2025 tarihleri arasında yayımlanan randomize kontrollü çalışmalar için PubMed ve Scopus veri tabanlarında sistematiik tarama yapılmıştır. Dahil edilme kriterleri; ≥ 60 yaş yetişkinler veya düşme riski yüksek olarak tanımlanan popülasyonlar (örneğin, düşme insidansının arttığı nörolojik hastalıklar), düşme önleme, denge, yürüme veya mobilitiyi hedefleyen VR temelli veya etkileşimli sanal eğitim müdahalesi, karşılaştırma grubu ve prospektif olarak raporlanmış düşme sonuçları (örneğin düşme insidansı, düşme oranı, düşen birey oranı veya insidans oranı) olarak belirlenmiştir. Toplam altı randomize ve RKÇ-türevi çalışma dahil edilmiştir. Müdahale türleri, düşme sonuç tanımları ve takip sürelerindeki heterojenite nedeniyle meta analiz yapılmamış; bunun yerine yapılandırılmış anlatımsal sentez uygulanmıştır. Yanlılık riski, Cochrane RoB 2 aracı kullanılarak değerlendirilmiştir.

Bulgular: Altı randomize ve RKÇ-türevi rapor dahil edilmiştir; örneklem büyüklükleri 26 ile 302 katılımcı arasında, mevcut takip süreleri ise 3 ile 12 ay arasında değişmiştir. Dahil edilen müdahaleler çoğunlukla yürüme, denge veya bilişsel-motor görevlerle entegre edilmiş immersif olmayan VR ya da etkileşimli sanal eğitim sistemlerine dayanmaktadır. Düşme sonuçları; düşme insidansı, düşme oranı, düşme sıklığı, düşme sayısı ve insidans oranı gibi farklı ölçütlerle raporlanmıştır. En olumlu etki sinyalleri, bilişsel-motor görevlerle birleştirilmiş bant üzerinde yürüme eğitimine entegre immersif olmayan VR sistemlerinde gözlenmiştir. Hiçbir çalışma yüksek yanlılık riski olarak değerlendirilmemiştir.

Sonuç: VR temelli müdahaleler, özellikle yapılandırılmış yürüme eğitimi içinde bilişsel-motor gereksinimleri entegre eden immersif olmayan sistemler kullanıldığında, yaşlı ve düşme riski yüksek yetişkinlerde düşmeyi önlemeye katkı sağlayabilir. Bununla birlikte, çalışma sayısının sınırlı olması, müdahale tasarımları ve düşme sonuçlarının raporlanmasındaki heterojenlik ile takip sürelerinin görece kısa olması nedeniyle bulgular dikkatli yorumlanmalıdır. Gelecek pragmatik randomize çalışmalarda standart düşme tanımları kullanılmalı ve prospektif olarak kaydedilmiş düşme insidansı veya düşme olayı temelli sonuçlar birincil sonlanım olarak değerlendirilmelidir.

Anahtar Kelimeler: Geriatri, Kazara Düşmeler, Sanal Gerçeklik, Yaşlı Bireyler, Rehabilitasyon

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INTRODUCTION

Falls represent one of the most significant geriatric syndromes worldwide, affecting approximately one-third of adults aged 65 years and older annually (1). Falls are associated with substantial morbidity, mortality, functional decline, institutionalization, and increased healthcare utilization (2). Beyond physical injury, falls often result in fear of falling, reduced mobility, and loss of independence, creating a downward spiral of frailty and inactivity (3).

Traditional fall prevention strategies have primarily focused on muscle strengthening, balance exercises, medication review, and environmental modifications (4). While these approaches demonstrate moderate effectiveness, many falls occur during cognitively demanding situations such as dual-task walking, obstacle negotiation, or divided attention activities (5). This has shifted attention toward interventions that target cognitive–motor integration rather than motor performance alone.

Cognitive–motor dual-task training has independently demonstrated reductions in fall frequency and improvements in gait variability, suggesting that executive control mechanisms play a critical role in fall prevention (6). These findings provide a theoretical basis for virtual reality (VR)-based and interactive virtual training interventions, which may enable simultaneous motor and cognitive engagement in controlled yet ecologically relevant environments.

Virtual reality (VR) refers to computer-generated environments that allow users to interact with simulated tasks through visual, auditory, or motion-based feedback (7). In rehabilitation settings, VR may be delivered through immersive systems, such as head-mounted displays or CAVE-based environments, or through non-immersive systems, such as screen-based, projection-based, Kinect-based, or exergame platforms (5,7-10). Although augmented reality (AR) and mixed reality (MR) were considered within the broader search strategy, the trials included in the present review were mainly based on VR, particularly non-immersive or interactive virtual training systems, rather than AR or MR (5,6,11-13).

More recent developments in immersive VR platforms aim to enhance ecological validity and sensorimotor

engagement, potentially strengthening reactive balance responses and adaptive gait control (10). However, despite increasing technological sophistication, fall incidence has not consistently been reported as a primary outcome in VR trials. Many studies instead rely on surrogate markers such as balance scales or fear-of-falling measures, limiting clinical interpretability (9,11).

Falls represent a high-frequency and high-impact adverse event in ageing populations, with direct implications for injury prevention, healthcare utilisation, functional independence, and quality of care. From a patient safety perspective, prospectively recorded fall outcomes constitute clinically meaningful endpoints reflecting preventable harm rather than intermediate performance change. Although numerous VR-based rehabilitation studies report improvements in balance performance, gait speed, or fear of falling, comparatively fewer trials have evaluated real-world fall events using prospective monitoring. By restricting inclusion to trials with prospective fall assessment, this review prioritises clinically meaningful outcomes and strengthens its relevance for geriatric practice and patient safety.

Given the critical importance of real-world fall reduction as a patient centred safety outcome, this systematic review aimed to evaluate the effects of VR-based interventions on prospectively recorded fall outcomes among older adults and high fall-risk adult populations.

MATERIALS AND METHOD

Study Design

This study was conducted as a systematic review of randomized controlled trials (RCTs) in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The objective was to synthesise evidence on the effects of VR-based and interactive virtual training interventions on prospectively recorded fall outcomes among older and high fall-risk adult populations.

Data Sources and Search Strategy

A comprehensive literature search was conducted in the PubMed (MEDLINE) and Scopus databases to identify

relevant studies published between January 2015 and December 2025. The search strategy combined controlled vocabulary terms (e.g., MeSH terms in PubMed) and free-text keywords related to virtual reality and extended reality technologies (“virtual reality”, “augmented reality”, “mixed reality”, “extended reality”, “VR”, “AR”, “MR”) and falls (“fall”, “falls”, “fall prevention”, “accidental falls”). Although the search strategy was intentionally broad enough to capture VR, AR, MR, and XR terminology, the final included studies were primarily based on VR or interactive virtual training systems.

Boolean operators (AND/OR) were applied to optimise sensitivity and specificity. Filters were applied to restrict results to randomized controlled trials and human studies where available. The reference lists of included articles were manually screened to identify additional relevant studies not captured by the electronic search. Only peer-reviewed articles published in English between January 2015 and December 2025 were included.

Eligibility Criteria

Studies were considered eligible if they met all predefined inclusion criteria. Specifically, the population comprised adults aged 60 years or older, or populations explicitly characterised as older adults, geriatric individuals, long-term care residents, or neurological groups identified as being at high risk of falls (e.g., Parkinson’s disease or multiple sclerosis). Eligible interventions included VR-based or interactive virtual training approaches, designed to address fall prevention, balance training, gait training, mobility enhancement, or cognitive–motor rehabilitation. These included non-immersive screen-based VR, projection-based VR, Kinect- or Wii-based exergaming, and other interactive virtual task environments. AR, MR, and broader XR-related terms were retained in the search strategy to ensure sensitivity; however, no included trial was primarily based on AR or MR. Comparator groups were required to receive conventional exercise, physiotherapy, usual care, treadmill training alone, or another non-virtual training intervention. Studies were included only if they prospectively reported actual fall events or fall-event metrics, such as fall incidence, fall rate, fall frequency, fall counts, proportion of fallers, recurrent falls, or incidence rate ratios.

Studies were excluded if they employed non-randomized designs, including observational studies, case series, case reports, study protocols, conference abstracts, editorials, or review articles. Trials that reported only surrogate performance-based outcomes, such as balance scales, gait parameters, or fear-of-falling measures, without prospective monitoring of real-world fall events were excluded. Accordingly, studies reporting only balance scales, mobility tests, gait parameters, fall-risk scores, or fear-of-falling measures without prospective fall-event monitoring were excluded, even when these outcomes were clinically relevant. Additionally, studies assessing falls exclusively during supervised intervention sessions, without post-intervention follow-up monitoring, were not considered eligible.

Study Selection and Data Extraction

All records identified through the database search were exported to a reference management software program, where duplicate entries were removed prior to screening. Study selection and data extraction were conducted by the author using a predefined structured checklist and a standardized extraction form. Because this review was conducted by a single reviewer, independent duplicate screening and extraction could not be performed. To reduce inconsistency, eligibility criteria were defined a priori, the same checklist was applied throughout title/abstract and full-text screening, and a sensitivity verification step was conducted during full-text assessment to confirm strict adherence to the predefined criteria. This methodological limitation is also acknowledged in the limitations section.

Data extraction was conducted using a standardized data extraction form designed specifically for this review. Extracted variables included bibliographic information (author and year of publication), study context (country and setting), sample size, participant characteristics, type of VR or interactive virtual training modality and detailed intervention characteristics, intervention duration and frequency, length of follow-up, operational definition and method of fall assessment, as well as primary fall-related outcomes and reported effect estimates. This structured approach aimed to ensure comprehensive and consistent capture of clinically relevant and methodologically comparable data across included trials.

Risk of Bias Assessment

The methodological quality of the included randomized controlled trials was assessed using the Cochrane Risk of Bias 2 (RoB 2) tool, which is specifically designed for evaluating bias in randomized studies. This tool examines potential sources of bias across five domains: bias arising from the randomization process, bias due to deviations from intended interventions, bias related to missing outcome data, bias in the measurement of outcomes, and bias in the selection of the reported result. Each domain was evaluated according to the signalling questions and algorithm provided in the RoB 2 guidance. Based on these domain-level assessments, an overall risk of bias judgment was assigned to each study and categorized as low risk of bias, some concerns, or high risk of bias. This approach was adopted to improve transparency and consistency in the assessment of internal validity across studies.

Data Synthesis

Interventions that used interactive virtual or exergame-based environments with simultaneous cognitive-motor task demands were considered eligible when they prospectively reported actual fall events and met all other inclusion criteria. Such studies were classified separately from non-immersive VR treadmill interventions during synthesis to avoid overgeneralisation.

Given the anticipated clinical, methodological, and statistical heterogeneity, including variability in fall definitions, reporting metrics (incidence vs rate vs IRR), and follow-up durations, pooling of effect sizes was not considered methodologically appropriate. Instead, a structured narrative synthesis was conducted to systematically summarise and interpret the findings. The synthesis focused on the direction and consistency of fall-related effects across trials, the specific characteristics of VR-based or interactive virtual training interventions associated with favourable outcomes, differences across population subgroups (e.g., community-dwelling older adults versus neurological high fall-risk populations), and the methodological quality and risk of bias of the included studies. During full-text assessment, a sensitivity check was performed to ensure consistent interpretation of fall outcome definitions and strict adherence to the predefined inclusion criteria, thereby enhancing internal consistency and methodological transparency of the review process.

RESULTS

Study Selection

The database search identified a total of 171 records (PubMed = 37; Scopus = 134). After removal of 27 duplicate records, 144 records remained. Following application of predefined filters (study design and publication year), 74 records were considered eligible for title and abstract screening. During title and abstract screening, 43 records were excluded for not meeting the inclusion criteria. The remaining 31 articles were retrieved for full-text assessment. After full-text evaluation, 25 studies were excluded, primarily due to absence of prospectively recorded fall outcomes, non-randomized design, or reporting of surrogate outcomes only. Ultimately, six randomized and RCT-derived reports fulfilled the eligibility criteria and were included in the final synthesis. The study selection process is illustrated in the PRISMA 2020 flow diagram (Figure I).

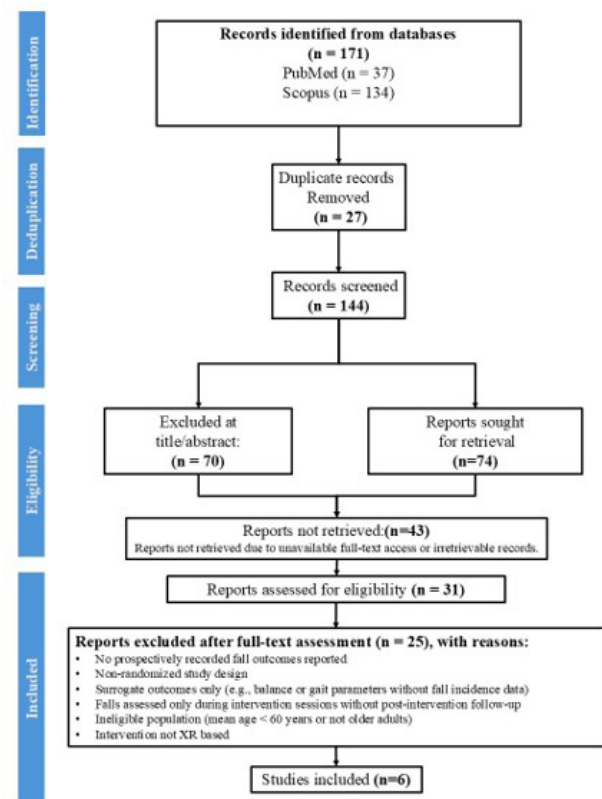


Figure I. PRISMA 2020 flow diagram of study identification, screening, eligibility assessment, and inclusion

The main reasons for exclusion at the full-text stage were the absence of prospectively recorded fall-event data, non-randomized study design, and reporting of surrogate performance outcomes (e.g., balance scores, gait parameters, or fear of falling measures) without quantitative fall event reporting.

Study Characteristics

The main characteristics of the included randomized and RCT-derived reports are presented in Table I. The six reports were published between 2015 and 2021, with sample sizes ranging from 26 to 302 participants. Most participants were community-dwelling older adults or high fall-risk neurological populations, including individuals with Parkinson's disease, mild cognitive impairment, multiple sclerosis, or HAM/TSP. Across studies involving older adults, mean participant age generally exceeded 65 years. Interventions predominantly involved non-immersive VR or interactive virtual training systems integrated with treadmill-based gait training, structured balance training, or cognitive-motor tasks. Intervention duration ranged from 6 weeks to 6 months, and follow-up ranged from

3 to 12 months where available. Falls were prospectively monitored using fall diaries, calendars, structured follow-up contacts, or predefined reporting systems.

Primary Fall Outcomes

Several included trials prospectively recorded fall-event outcomes using fall diaries, calendars, or structured follow-up procedures over 3–6 months (5,8,11-13). Among these, the V-TIME trial provided the strongest evidence because fall rate was prespecified and prospectively monitored over six months (5). The trial demonstrated a significant reduction in fall rate in the VR plus treadmill group compared with treadmill training alone. The magnitude of effect was particularly notable among participants at higher baseline fall risk.

Pelosin et al. (11) also reported a significant reduction in fall frequency at six-month follow-up in individuals with Parkinson's disease undergoing multimodal VR treadmill training. Similarly, Molhemi et al. (13) observed fewer falls at three-month follow-up in the VR group compared with conventional balance training in patients with multiple sclerosis.

Table I. Characteristics of included randomized and RCT-derived studies evaluating VR-based or interactive virtual training interventions for fall prevention

Study (author, year)	Country / setting	Sample	Population	VR or	Duration / follow-up	Fall outcome	Main findings
Mirelman et al. (V-TIME) (5)	Multicenter	Randomized n=302; analysed n=282. TT: 73.3±6.4 years, female 52/136; TT+VR: 74.2±6.9 years, female 48/146. High fall-risk older adults with idiopathic falls, MCI, or PD.	High fall-risk older adults with idiopathic falls, MCI, or PD	Non-immersive VR and treadmill	6 weeks / 6 months	Fall incident rate; falls calendar; IRR	TT and VR significantly reduced fall rate compared with treadmill training alone
Eggenberger et al. (6)	Switzerland	Randomized n=89; analysed n=71. DANCE: 77.3±6.3 years, female 58.3%; MEMORY: 78.5±5.1 years, female 72.7%; PHYS: 80.8±4.7 years, female 64.0%. Community-dwelling older adults >70 years.	Community-dwelling older adults	VR video game dancing or treadmill memory training; all groups received strength/ balance exercises	6 months / 12 months	Fall frequency; secondary outcome	Fall frequency decreased globally across groups; no clear intervention-specific superiority
Study (author, year)	Country / setting	Sample	Population	VR or Interactive Virtual Training Modality	Duration / follow-up	Fall outcome	Main findings

Table I (Continued). Characteristics of included randomized and RCT-derived studies evaluating VR-based or interactive virtual training interventions for fall prevention

Del Din et al. (8)	Multicenter	Secondary analysis of V-TIME; n=275. Older fallers: 75.93±6.22 years, female 78%; MCI: 78.03±6.21 years, female 68%; PD: 71.68±6.43 years, female 37%.	High-risk older adults	Secondary analysis of V-TIME; parent	6 weeks / 6 months	Falls Rate to Activity Index; falls normalized to activity exposure	FRA index decreased without concurrent reduction in walking activity
Pelosin et al. (11)	Italy	n=39; TT n=22, TT+VR n=17. TT: 71.9±4.1 years, female 15/22; TT+VR: 73.2±3.6 years, female 11/17. Older fallers, including PD and older adults.	Older fallers (PD predominant)	Cognitive–motor VR-supported training	6 weeks / 6 months	Number of falls; falls calendar	TT and VR reduced number of falls; fall reduction correlated with SAI change
Patrício et al. (12)	Brazil	n=26; TCG n=13, CTG n=13. TCG: 49.1±11.8 years, female 10/13; CTG: 52.1±7.5 years, female 7/13. Adults with HAM/TSP.	Adults with HAM/TSP	VR balance gaming	10 weeks / 20-week crossover assessment		Fall occurrence decreased after the intervention sequence; exploratory due to small crossover sample
Molhemi et al. (13)	Iran	n=39; VR n=19, control n=20. Adults with multiple sclerosis.	Adults with MS	VR balance training	6 weeks / 3 months	Fall diary; number of falls and fallers	Number of falls was significantly lower in the VR group at 3-month follow-up; number of fallers was not significantly different

CTG: Control-test group, FRA: Falls Rate to Activity, HAM/TSP: HTLV-1-associated myelopathy/tropical spastic paraparesis, IRR: Incidence rate ratio, MCI: Mild cognitive impairment, MS: Multiple sclerosis, PD: Parkinson's disease, PHYS: Physical training, SAI: Short afferent inhibition, TCG: Test-control group, TT: Treadmill training, VR: Virtual reality

Secondary Fall Outcomes

In one smaller trial involving individuals with HAM/TSP, fall frequency decreased following VR-based gaming interventions; however, the short follow-up period and limited sample size reduced statistical power (12). Eggenberger et al. (6) although not a treadmill-based VR intervention, used an interactive virtual reality video game dancing approach with simultaneous cognitive–motor training and therefore supported the mechanistic rationale for interactive virtual training approaches targeting executive–motor integration.

Risk of Bias Assessment

Risk of bias was evaluated using the Cochrane RoB 2 (Table II) tool across five domains: randomization process, deviations from intended interventions, missing outcome data, measurement of the outcome, and selection of the reported result.

No study was classified as having high risk of bias. One trial demonstrated overall low risk of bias (5), while the remaining studies were judged as having some concerns, primarily related to allocation concealment procedures and potential deviations from intended interventions. Fall-event outcome measurement was generally considered at low risk due to prospective monitoring procedures.

Table II. Risk of bias assessment of included randomized and RCT-derived reports (Cochrane RoB 2 Tool)

Study	Randomization	Deviations	Missing data	Outcome	Selective Reporting	Overall risk
Mirelman et al. (5)	Low	Some concerns	Low	Low	Low	Low
Eggenberger et al. (6)	Low	Some concerns	Some concerns	Low	Low	Some concerns
Del Din et al. (8)	Some concerns	Some concerns	Low	Low	Low	Some concerns
Pelosin et al. (11)	Some concerns	Some concerns	Low	Low	Low	Some concerns
Patrício et al. (12)	Some concerns	Some concerns	Some concerns	Low	Low	Some concerns
Molhemi et al. (13)	Some concerns	Some concerns	Low	Low	Low	Some concerns

Effect Patterns Across Studies

Across the six included trials, four studies reported reductions in falls or fall-event metrics favouring VR-based interventions compared with control conditions, although statistical significance varied depending on study size and population. The strongest and most consistent effects were observed in treadmill-based gait training augmented with non-immersive VR incorporating cognitive–motor challenges.

Trials conducted in neurological populations (Parkinson’s disease and multiple sclerosis) demonstrated signals of fall reduction, whereas multicomponent exergame-based interventions without structured gait integration showed less consistent effects.

DISCUSSION

This systematic review synthesized evidence from six randomized and RCT-derived reports evaluating VR-based and interactive virtual training interventions in reducing prospectively recorded fall outcomes among older and high fall-risk adult populations. Overall, the findings suggest a potential fall-reduction signal, particularly for non-immersive VR interventions integrating cognitive–motor challenges within structured gait training. However, this signal should be interpreted cautiously because of the small number of eligible trials, heterogeneity in fall outcome reporting, and relatively short follow-up periods (5,8,11,13).

The clinical benefit of VR-based and interactive virtual training interventions appears to extend beyond conventional balance training paradigms. Traditional fall prevention programs predominantly target muscle strength and postural control (4), whereas VR-based environments can enable simultaneous cognitive engagement, obstacle negotiation, and adaptive gait modulation. The demonstrated efficacy of cognitive–motor dual-task paradigms in reducing fall events (6) provides a mechanistic foundation for these findings. Experimental work combining motor–cognitive tasking within complex virtual environments has shown reductions in dual-task walking costs, further supporting the neurophysiological plausibility of cognitively enriched gait training (14). Falls frequently occur under cognitively demanding conditions, and interventions addressing executive–motor integration may therefore be more effective than motor training alone.

Importantly, fall reduction should be interpreted within the framework of activity exposure. Del Din et al. (8) demonstrated that increased mobility does not inherently increase fall risk when adaptive motor control improves. VR-based or interactive virtual training interventions may therefore enhance safe ambulation rather than merely restricting activity levels. This distinction is clinically critical, as fall prevention strategies must avoid inadvertently promoting sedentary behaviour.

Although the number of trials is limited, a recurring observation is that interventions integrating cognitive–motor components tend to show more favourable effects

on fall outcomes than those focusing on balance alone. VR-based treadmill paradigms and related perturbation-based approaches simulate complex real-world scenarios in safe and controlled settings, potentially enhancing reactive balance responses and adaptive gait control. Outside the XR field, perturbation-based dual-task treadmill training has demonstrated reductions in daily life falls and fallers over extended follow-up, reinforcing the clinical relevance of ecologically valid gait challenges (15). This aligns with contemporary models of fall risk that emphasise executive function, attentional allocation, and cortical–subcortical integration as central determinants of safe mobility.

Neurological high fall-risk populations, including Parkinson’s disease and multiple sclerosis, also demonstrated favourable signals of benefit in included trials (11,13). These populations are characterised by impaired gait automaticity and increased dual-task interference, suggesting that cognitive–motor rehabilitation delivered through VR-based or interactive virtual training systems may be particularly relevant where executive–motor coupling is compromised. Supporting evidence from additional RCTs in Parkinson’s disease indicates that non-immersive VR exergaming improves balance and fall-risk indices compared with conventional physiotherapy (16), although these studies predominantly report surrogate outcomes rather than prospectively recorded fall outcomes.

These findings are especially pertinent within geriatric populations characterised by multidimensional vulnerability. As falls constitute a core geriatric syndrome closely intertwined with frailty, sarcopenia, multimorbidity, and polypharmacy, VR-based or interactive virtual training cognitive–motor interventions may have implications extending beyond fall prevention alone, potentially contributing to functional resilience and sustained mobility preservation.

Although immersive VR and related digital rehabilitation technologies are evolving rapidly (9,10), most included trials utilised non-immersive platforms. Emerging immersive paradigms, including CAVE-based cognitive motor systems, have begun to assess fall outcomes in cognitively vulnerable populations such as older adults with mild cognitive impairment (17). Augmented reality

telerehabilitation platforms have demonstrated feasibility and clinically meaningful improvements in gait and balance, though fall incidence remains underexplored (18). Longer-duration VR trials in institutionalised elderly populations have reported improvements in anti-fall ability and, in some cases, reductions in fall events over 12 months, suggesting potential sustainability when training exposure is sufficient (19). Nevertheless, robust comparative trials evaluating immersive versus non-immersive paradigms with standardised fall outcome reporting are warranted.

Methodologically, this review deliberately restricted inclusion to trials prospectively measuring actual fall events. Many VR and related digital rehabilitation studies report improvements in surrogate outcomes such as balance scores, gait speed, functional mobility, or fear of falling without assessing real-world fall outcomes. For example, trials comparing virtual reality, traditional balance training, and combined exercise approaches have demonstrated significant gains in strength and mobility (20), VR-based balance interventions have improved BBS and TUG scores in institutionalised elderly populations (21), and vestibular VR rehabilitation has shown sustained improvements in mobility and dizziness-related disability (22). Similarly, perturbation-based balance programmes (23), motor imagery combined with VR (24,25), and home-based VR physiotherapy systems (26) primarily report performance-based outcomes. While clinically meaningful, such surrogate improvements do not necessarily translate into reduced fall outcomes. By focusing exclusively on prospectively recorded falls, the present review enhances clinical relevance and patient-centred interpretation.

Nevertheless, several limitations must be acknowledged. The overall number of eligible trials was limited, and substantial heterogeneity in intervention modalities, follow-up durations, and fall measurement approaches precluded quantitative meta-analysis. Sample sizes varied considerably, and follow-up periods were relatively short (3-12 months), limiting inference regarding long-term sustainability of effects. Furthermore, fall definitions and monitoring methods differed across studies. Standardization of fall reporting, preferably using prospective diaries supplemented by structured follow-up contacts, is essential to improve comparability and facilitate future meta-analyses.

Although no study was judged to have high risk of bias, most trials presented some concerns, particularly regarding allocation concealment and deviations from intended interventions. These methodological considerations highlight the need for rigorously designed adequately powered multicenter trials prioritizing fall incidence or fall-event outcomes as primary endpoints.

Despite rapid technological expansion in VR and related digital rehabilitation applications, rigorous randomized trials reporting real-world fall outcomes remain scarce. Feasibility studies indicate that VR-based exercise platforms are generally safe and acceptable, with high adherence and no intervention-related falls during training sessions (27), supporting their implementation potential. However, definitive evidence of sustained fall reduction across diverse settings is still required. This gap suggests that future research should move beyond performance-based measures and focus more consistently on real-world fall outcomes.

Policy Implications

From a clinical and health systems perspective, VR-based or interactive virtual training cognitive–motor gait training should currently be considered a technology-enabled adjunct within multimodal fall prevention pathways rather than a standalone replacement strategy. By replicating real-world mobility demands under controlled conditions, VR-based or interactive virtual training interventions may enhance ecological validity while maintaining patient safety.

However, wider integration into rehabilitation services requires robust evaluation of cost-effectiveness, scalability across care settings, workforce training requirements, digital infrastructure readiness, and long-term sustainability. Policymakers and health system leaders should prioritise pragmatic trials incorporating economic analyses and implementation science frameworks to determine real-world feasibility and value.

Given that falls constitute a core geriatric syndrome associated with frailty, sarcopenia, cognitive decline, and polypharmacy, VR-based or interactive virtual training cognitive–motor interventions may offer a multidimensional preventive approach within comprehensive geriatric care models. When embedded within structured quality improvement and patient safety

programmes, VR-based and interactive virtual training interventions may support proactive risk mitigation strategies aimed at reducing preventable harm among ageing and high fall-risk populations.

Study Limitations

A major strength of this review is its strict focus on randomized controlled trials reporting prospectively recorded fall outcomes, thereby prioritising clinically meaningful outcomes over surrogate performance measures. The use of PRISMA 2020 guidelines and the Cochrane RoB 2 tool further enhances methodological transparency.

However, several limitations should be acknowledged. First, only two databases were searched, which may have resulted in omission of relevant studies. Second, study selection, data extraction, and risk of bias assessment were conducted by a single reviewer; therefore, independent duplicate screening and extraction could not be performed. To mitigate this limitation, predefined eligibility criteria, a structured checklist, and a sensitivity verification step during full-text assessment were used. Third, the number of eligible trials was small, and clinical heterogeneity limited quantitative synthesis. Fourth, most included trials had modest sample sizes and short follow-up durations, restricting inference regarding long-term effectiveness.

CONCLUSION

VR-based interventions, particularly those integrating cognitive–motor demands within structured gait training, demonstrate promising signals for reducing real-world fall outcomes among older and high fall-risk adults. Nevertheless, the limited number of trials and methodological heterogeneity warrant cautious interpretation. Robust, standardised, and pragmatic research is needed to determine the long-term clinical and health system impact of VR-based technologies in fall prevention. Future trials should prioritise prospectively recorded fall incidence or fall-event outcomes as primary endpoints rather than relying solely on performance-based surrogate measures.

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Use of Artificial Intelligence

No artificial intelligence (AI) technologies or AI-assisted tools were utilized in the preparation or production of this study.

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