Systematic Review/Meta-Analysis

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Effects of Virtual Reality-Based Exercise Training on Risk of Falling, Walking Capacity, and Quality of Life in Healthy Older Adults: A Systematic Review and Meta-Analysis Research

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Abstract

This systematic review and meta-analysis aimed to assess virtual reality (VR)-based exercise effects on walking capacity, fall risk, and quality of life in healthy older adults. Five databases were searched up to January 2025. From 56 trials involving 2927 participants, VR improved six-minute walk distance (MD = 24.59, 95% CI: 20.90–28.28, $p < 0.00001$), gait speed (MD = 0.04, 95% CI: 0.01–0.07, $p = 0.02$), and Timed Up-and-Go test (MD = −0.67, 95% CI: −1.08 to −0.25, $p = 0.001$), while reducing fear of falling (SMD = −0.67, 95% CI: −1.01 to −0.33, $p = 0.0001$). Quality-of-life gains included physical (MD = 0.31, $p = 0.009$), environmental (MD = 0.42, $p = 0.01$), psychological (MD = 0.47, $p = 0.003$), and social health (MD = 0.31, $p = 0.004$). VR-based exercise is an effective, engaging tool to enhance mobility, lower fall risk, and promote functional independence and psychosocial well-being.

Keywords

exercise interventions, functional mobility, healthy aging, immersive technology, physical function

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What this paper adds

- VR-based exercise enhances walking capacity (e.g., 6-MWD and gait speed) and reduces fall risk (e.g., TUG and FES) in healthy older adults, supporting physical function preservation.
- Improved functional mobility and balance confidence through VR may contribute to preventing age-related declines, as evidenced by TUG and FES gains.
- This study provides robust evidence of quality-of-life improvements (e.g., physical and social health), highlighting VR's broader psychosocial benefits.

Application of study findings

- Future research should explore VR's long-term effects on mobility, balance, and fall prevention in aging populations.
- Integrating VR exercise into community wellness programs could enhance engagement and accessibility for older adults.
- Policy efforts should promote training for healthcare providers to incorporate VR-based interventions into routine care, supporting healthy aging.

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Introduction

The 21st century has witnessed a significant rise in the global population of older adults, presenting challenges such as reduced functional mobility, heightened fall risk, and diminished independence (Corregidor-Sánchez et al., 2020; Khan, 2019; Shema et al., 2014; Vasodi et al., 2023). Falls remain a primary cause of injury among older adults, often leading to reduced social participation, fear of falling, and compromised quality of life (Alikhajeh et al., 2023; Rivasi et al., 2020; Sung et al., 2020; Vazirian et al., 2017). Addressing these issues requires accessible interventions that enhance mobility, reduce fall-related concerns, and promote well-being, ultimately supporting older adults' ability to remain active in their communities (Nejatian Hoseinpour et al., 2025; Niyazi et al., 2024; Shema et al., 2014).

Regular physical activity is a well-established pillar of healthy aging, offering benefits such as improved balance, muscle strength, and cognitive function (Setayesh & Mohammad Rahimi, 2023). These gains are commonly measured using validated tools like the Timed Up-and-Go test (TUG), Berg Balance Scale (BBS), and Falls Efficacy Scale (FES-I) (Liu et al., 2022; Meekes & Stanmore, 2017). However, traditional exercise regimens can be challenging for older adults to sustain, especially for those living independently or with limited mobility (Pacheco et al., 2020; Yen & Chiu, 2021). Furthermore, access to structured exercise programs may be limited by transportation barriers, cost, or lack of tailored services in community settings. Recent advances in virtual reality (VR)-based exercise programs provide a promising, engaging alternative to overcome these barriers and promote physical activity among older adults (Hall et al., 2016).

VR-based exercise, often delivered through exergames, immerses users in interactive environments that require active participation, supporting motor skill development and functional improvement (Høeg et al., 2021; Van Diest et al., 2013; Yoo et al., 2020). These programs frequently target balance, a critical factor in reducing fall risk and improving coordination (Anderson & Lane, 2020; Schoberer & Breimaier, 2020). Research indicates that older adults engaging in VR-based interventions experience enhanced balance, greater confidence in daily activities, and reduced fear of falling (Gomes et al., 2018; Montero-Alía et al., 2019; Rendon et al., 2012). Moreover, VR interventions offer psychological benefits, such as elevated mood and improved quality of life, particularly for older adults in care settings (Skjæret et al., 2016; Zhang & Kaufman, 2016). In addition to these outcomes, the relative affordability and scalability of VR systems enhance their feasibility for community-based applications, especially in aging populations.

The growing field of Clinical Virtual Reality highlights VR's potential in rehabilitation and preventive health (Rizzo et al., 2011). Prior reviews have demonstrated VR's efficacy in improving balance (Molina et al., 2014; Pacheco et al., 2020), alleviating depressive symptoms, and enhancing mental and physical health outcomes in older adults (Drazich et al., 2020; Li et al., 2016; Vasodi et al., 2023). However, these studies often focus on older adults with conditions like Parkinson's disease (Ribas et al., 2017), dementia (Mura et al., 2018; Van Santen et al., 2018), or stroke (Cano Porras et al., 2018), rather than healthy older adults.

A critical knowledge gap persists regarding the broader impact of VR-based exercise on healthy aging. While some studies have explored specific outcomes like balance or reaction time, few have comprehensively assessed functional measures such as walking capacity, fall risk, and quality of life in healthy older adults (Donath et al., 2016; Neri et al., 2017; Tahmosybayat et al., 2018). This review defines "older adults" as individuals aged 60 years and older, consistent with thresholds commonly used by global health organizations such as the World Health Organization (World Health Organization, 2002). By examining these outcomes, VR-based interventions could emerge as a proactive, evidence-based approach to sustain independence and enhance quality of life in this population, with potential implications for clinical practice and aging policy.

This systematic review and meta-analysis aimed to address this gap by synthesizing evidence on the effects of VR-based exercise in healthy older adults aged 60 years and older. Specifically, it examines the impact on walking capacity, fall risk, and quality of life. The findings seek to inform the integration of VR technology into preventive health strategies, offering practical insights for clinicians, caregivers, and policymakers to support healthy aging and community engagement in this growing demographic.

Methods

This systematic review adhered to the PRISMA (Preferred Reported Items for Systematic Review and Meta-Analysis) Guidelines (Page et al., 2021). The study is registered with the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number CRD42024533739. This review was conducted in accordance with the pre-specified protocol.

Eligibility Criteria (PICOS Framework)

A structured set of inclusion and exclusion criteria was developed using the PICOS framework:

Participants

Healthy older adults aged 60 years or older. "Healthy" was defined as community-dwelling individuals without diagnosed neurological, musculoskeletal, cardiovascular, metabolic, or cognitive conditions that could affect balance, gait, or independent functioning.

Intervention

VR-based exercise programs that utilized interactive virtual reality platforms or exergaming systems designed to promote physical activity. Eligible interventions featured immersive or non-immersive VR formats (e.g., head-mounted displays, motion sensors, screen-based systems such as Nintendo Wii, and Xbox Kinect), and required active participant engagement. Both supervised (e.g., in rehabilitation or clinical settings) and unsupervised (e.g., home-based) interventions were included, provided safety measures were reported. Programs varied in exercise intensity, with most targeting balance, coordination, gait, or lower-limb strength, and intensity was categorized as light to moderate based on descriptions of session frequency, duration, and exertion levels.

Comparator

Control conditions varied across studies and included: (1) no intervention or usual routine activities, (2) education-based interventions (e.g., health booklets or cognitive training), and (3) conventional or low-intensity physical activities such as walking, stretching, or traditional senior fitness programs. Despite this heterogeneity, all comparators lacked immersive VR components, and thus served as appropriate controls for isolating the effects of VR-based interventions.

Outcomes

Walking capacity (e.g., gait speed, cadence, and 6-minute walk distance [6-MWD]), fall risk (e.g., 8-foot Up-and-Go test [8-FUG], FES, and TUG), and quality of life.

Study Design

Randomized controlled trials (RCTs) and controlled trials with randomized pretest-posttest designs.

Exclusion criteria included abstracts, conference proceedings, reviews, protocols, non-English studies, and studies reporting only between-group posttest outcomes without pretest data.

Data Sources and Search Strategy

A systematic search was conducted to identify RCTs evaluating VR-based exercise in older adults, compared with alternative exercise programs or inactive controls. Databases searched included PubMed, CINAHL, Web of Science, Cochrane, and Scopus, covering all entries up to January 10, 2025. Search terms included “virtual reality exercise,” “exercise,” and “RCT,” combined using Boolean operators. Reference lists of relevant studies and reviews were hand-searched.

Two assessors independently screened records, retrieved full texts for uncertain cases, and resolved disagreements through discussion or third-party adjudication. Detailed search strategies are provided in Supplemental Table S1.

Data Extraction

Two researchers (F.OS and F.M) independently extracted data using a standardized data extraction form developed for systematic reviews (Higgins JPT et al., 2024). This form captured key data elements aligned with Cochrane recommendations, including author, year, country, sample size, age, gender, intervention frequency, duration, outcome measures, and effect estimates (mean differences (MD) and standard deviations (SDs)). Data in formats other than mean and SD (e.g., median and range) were recorded and converted using established methods to ensure uniformity in meta-analysis (Higgins et al., 2003). Discrepancies were resolved by consensus to enhance reliability.

Study Quality and Risk of Bias

Study quality was assessed using the 15-point Tool for the Assessment of Study Quality and Reporting in Exercise (TESTEX) scale, a tool tailored for exercise interventions (Smart et al., 2015). The scale includes criteria for study quality and reporting, assigning scores out of 15. Scores ≥10 indicated good quality (Gilson et al., 2019). Two researchers (M.T and V.S) independently rated studies, with a third researcher (B.AS) resolving discrepancies.

In addition, the risk of bias in each included study was evaluated using the Cochrane Risk of Bias tool version 2.0 (Sterne et al., 2019). The assessment was based on several methodological criteria, including sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessors, completeness of follow-up, and selective reporting. Two reviewers (F.OS and B.AS) independently performed the risk of bias assessments, resolving any disagreements through discussion.

Statistical Analyses and Meta-analyses

Meta-analyses and forest plots were generated utilizing Review Manager (RevMan) 5 (Collaboration, 2014). For outcomes with significant heterogeneity ($I^2 > 50\%$), a random-effects model with inverse variance methods was applied to calculate MD and 95% confidence intervals (CI), accounting for variability across studies (Hedges & Vevea, 1998). A fixed-effect model was used when heterogeneity was low ($I^2 < 50\%$), ensuring appropriate statistical pooling. The DerSimonian-Laird estimator was employed to estimate variance in random-effects models. Mean and SD values were extracted to calculate changes from baseline to post-intervention. When SD was unavailable, it was derived from sample size, p-values, or 95% CI; standard error of the mean (SEM) was converted to SD as needed (Higgins et al., 2003). Data from figures were extracted using GetData Graph Digitizer when not provided in text or tables, with efforts made to contact authors for missing data (Rohatgi, 2021).

Heterogeneity was assessed using the I^2 statistic, with values >50% indicating considerable heterogeneity (Higgins & Green, 2008). Publication bias was evaluated via funnel plots, and sensitivity analysis assessed each trial's influence on overall results. A significance level of 5% was set for effect size.

Additionally, to explore sources of heterogeneity in outcomes with sufficient data (≥10 trials), meta-regression analyses were conducted using Comprehensive Meta-analysis for gait speed, TUG, and FES. The following moderator variables were included: intervention duration (weeks), session frequency (sessions per week), participants' gender composition (all-female vs. mixed), and control group activity level (active vs. passive).

Results

Study Selection and Characteristics

The initial search identified 1,354 records from database and reference searches. After removing 367 duplicates, 987 records were screened. Of these, 916 were excluded based on title and abstract review, leaving 71 full-text articles for eligibility assessment. After reviewing these, 15 articles were excluded for the following reasons: participants were under 60 years, the study used an active comparator that didn't meet our criteria (such as another VR program or high-intensity exercise), there was no control group, or the article was a conference paper or protocol. These exclusions followed our eligibility criteria, which allowed only comparators like usual care, no intervention, or low-intensity exercise. Finally, 56 trials (Abd El-Kafy et al., 2024; Adcock et al., 2020; Babadi & Daneshmandi, 2021; Bieryla, 2016; Bieryla & Dold, 2013; Chao, 2014; Cicek et al., 2020; Daniel, 2012; De Queiroz et al., 2017; Delbaere et al., 2021; Duque et al., 2013; Eggenberger et al., 2015, 2016; Fakhro et al., 2020; Fu et al., 2015; Gomes et al., 2018; Gschwind et al., 2015; Htut et al., 2018; Jorgensen et al., 2013; Jung et al., 2015; Karahan et al., 2015; Keogh et al., 2014; Konstantinidis et al., 2014; Lai et al., 2013; Lauzé et al., 2017; LAZAR, 2023; A. Lee et al., 2014; K. Lee, 2020; M. Lee et al., 2015; Y. Lee et al., 2017; Lyubenova et al., 2023; Maillot et al., 2012, 2014; Merriman et al., 2015; Nicholson et al., 2015; Orsega-Smith et al., 2012; Padala et al., 2012; Park et al., 2015; Peng et al., 2020; Phirom et al., 2020; Pichierri et al., 2012; Pluchino et al., 2012; Ray et al., 2012; Rendon et al., 2012; Rica et al., 2020; Sápi et al., 2019; Sato et al., 2015; Schättin et al., 2016; Schoene et al., 2013; Schwenk et al., 2014; Singh et al., 2012; Stanmore et al., 2019; Tsang & Fu, 2016; Yang et al., 2020; Yeşilyaprak et al., 2016; Zahedian-Nasab et al., 2021) involving 2,927 participants were included in the meta-analysis (Figure 1).

Characteristics of the Included Studies

The included studies were conducted across various countries, with the majority (11 out of 56) based in the United States. Sample sizes ranged from 10 to 232 participants, with ages spanning from 60.3 to 87.2 years. Table 1 provides detailed characteristics of the included studies. Quality of life was assessed using the Medical Outcomes Survey Short Form 36 (SF-36) in one study, the Quality of Life-Alzheimer's disease scale in one study, and the WHOQOL-BREF questionnaire in two studies.

Meta-Analysis

Walking Capacity

A meta-analysis of seven trials (264 participants) demonstrated a statistically significant improvement in 6-MWD following VR-based exercise training (MD = 24.59, 95% CI: 20.90 to 28.28; $p < 0.00001$), with high heterogeneity ($I^2 = 78\%$; Figure 2A).

A meta-analysis of 13 trials (569 participants) revealed a statistically significant improvement in gait speed with VR-based exercise (MD = 0.04, 95% CI: 0.01 to 0.07; $p = 0.02$), with no heterogeneity ($I^2 = 0\%$; Figure 2B). The meta-regression analyses revealed that none of the assessed variables significantly contributed to the heterogeneity in gait speed. Specifically, control group activity (Q = 2.68, $p = 0.61$), study duration (Q = 0.49, $p = 0.49$), the number of sessions per week (Q = 0.24, $p = 0.62$), and gender (Q = 0.65, $p = 0.42$) did not significantly influence the effects of VR-based exercise training on gait speed (Supplemental Tables S2-5). Sensitivity analysis showed that when the studies by Lauze et al. (2018) and Nicholson et al. (2015) were removed, the effect of VR-based exercise interventions became insignificant (MD = 0.03, 95% CI: –0.00 to 0.06; $p = 0.07$; and MD = 0.03, 95% CI: –0.01 to 0.06; $p = 0.11$, respectively).

A meta-analysis of seven trials (344 participants) showed a non-significant improvement in cadence following VR-based exercise training (MD = –0.23, 95% CI: –1.13 to 0.68; $p = 0.63$), with low heterogeneity ($I^2 = 22\%$; Figure S1).

Risk of Falling

A meta-analysis of 32 trials (34 arms, 1283 participants) showed a statistically significant reduction in the TUG test with VR-based exercise (MD = –0.67, 95% CI: –1.08 to –0.25; $p = 0.001$), with moderate heterogeneity ($I^2 = 57\%$; Figure 3a). The meta-regression analyses revealed that none of the assessed variables significantly contributed to the heterogeneity in gait speed. Specifically, control group activity (Q = 5.15, $p = 0.40$), study duration (Q = 1.70, $p = 0.19$), the number of sessions per week (Q = 0.66, $p = 0.42$), and gender (Q = 2.95, $p = 0.23$) did not significantly influence the effects of VR-based exercise training on TUG (Supplemental

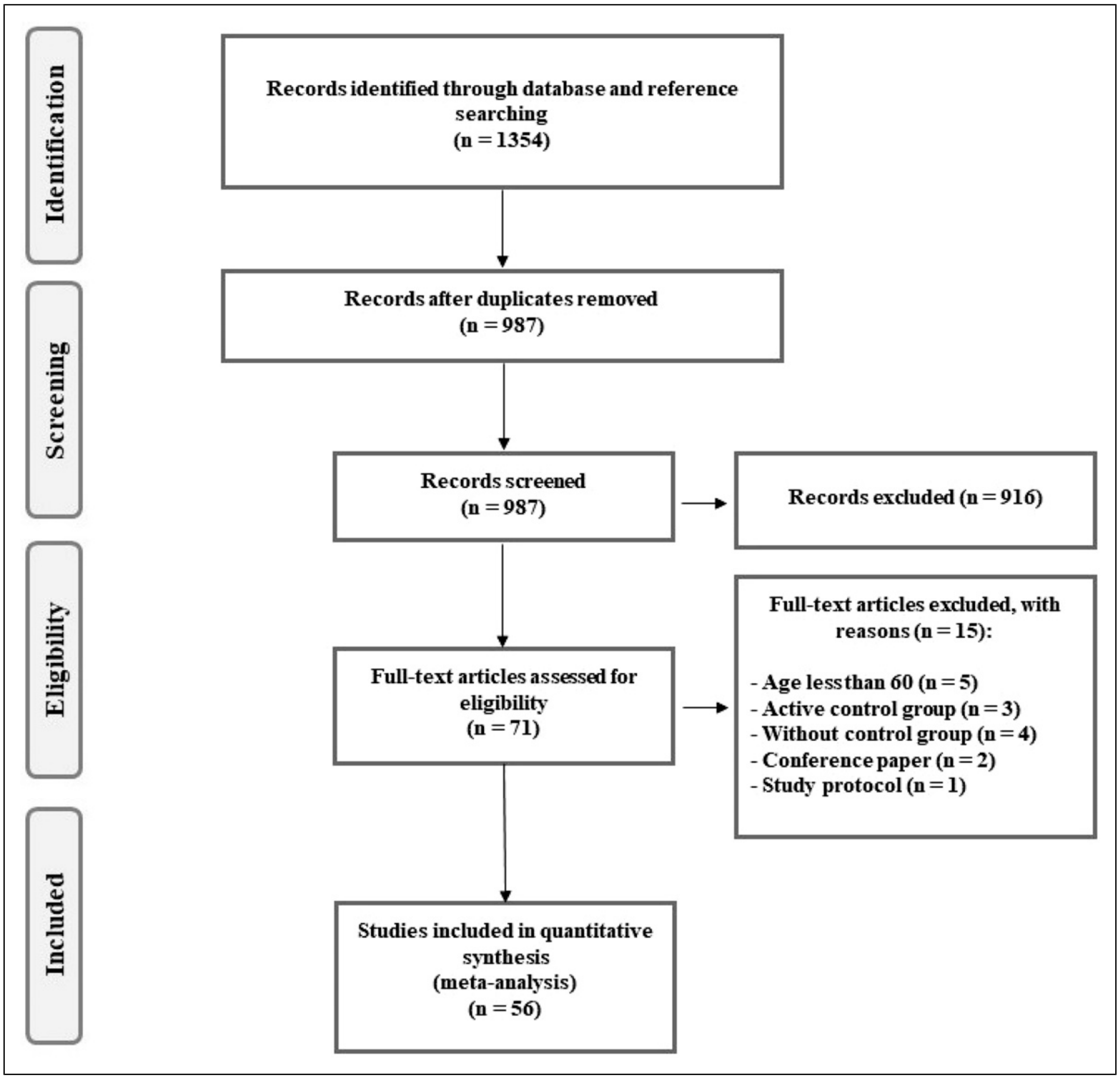

Figure 1. PRISMA flow diagram (search period: database inception to January 10, 2025).

Tables S6-9). Sensitivity analysis indicated that excluding individual studies did not affect the statistical significance, reinforcing the robustness of the findings.

A meta-analysis of 18 trials (19 arms, 969 participants) indicated a statistically significant reduction in FES scores with VR (SMD = –0.67, 95% CI: –1.01 to –0.33; $p = 0.0001$), with high heterogeneity (I^2 = 84%; Figure 3b). The meta-regression analyses revealed that none of the assessed variables significantly contributed to the heterogeneity in FES. Specifically, control group activity (Q = 6.88, $p = 0.44$), study duration (Q = 0.00, p = 0.95), the number of sessions per week (Q = 1.69, $p = 0.19$), and gender (Q = 2.25, $p = 0.32$) did not significantly influence the effects of VR-based exercise training on FES (Supplemental Tables S10-13). Sensitivity analysis showed no statistically significant differences when individual studies were excluded, further supporting the robustness of these findings.

A meta-analysis of eight trials (503 participants) revealed that VR-based exercise training had no significant effect on 8-FUG time (MD = –1.70, 95% CI: –3.78 to 0.38; p = 0.11), with high heterogeneity (I^2 = 99%; Figure S2).

Quality of Life

A meta-analysis of six trials (369 participants) demonstrated a non-significant improvement in the total SF-36 score with VR-based exercise (MD = 0.15, 95% CI: –0.05 to 0.36; p = 0.15), with no heterogeneity (I^2 = 0%; Figure S3).

A meta-analysis of four trials (346 participants) revealed a statistically significant improvement in environmental health scores following VR-based exercise (MD = 0.42, 95% CI: 0.09 to 0.75; p = 0.01), with low heterogeneity (I^2 = 37%; Figure 4A).

Table 1. Details of included studies (search period: database inception to January 10, 2025)

		Participants			Intervention		
Author; year	Country	*N*	Age: Mean (SD)	Gender	Experimental group	Control group	Outcome measures
Abd el-kafy, 2023	Saudi Arabia	***n*** **= 60** **EXP = 27** **CON = 27**	**EXP:** 66.53 (3.82) **CON:** 65.43 (4.28)	Both	4 week/3 times training on the C-Mill virtual reality treadmill	C-Mill treadmill which included regular walking without any virtual reality games or visual projections	6-MWT, Velocity, Cadence
Adcock, 2020	Spain	***n*** **= 37** **EXP = 15** **CON = 16**	**EXP:** 77.00 (6.40) **CON:** 70.90 (5.00)	Female	16 weeks/3 times exergame training including Tai Chi-inspired exercises, dancing and step-based cognitive games	Usual care	Gait speed
Bieryla, 2013	USA	***n*** **= 12** **EXP = 5** **CON = 5**	**EXP:** 82.50 (1.60) **CON:** 80.50 (7.80)	Both	3 week/3 times using Nintendo's Wii fit game	Normal activities	TUG
Bieryla, 2015	Switzerland	***n*** **= 13** **EXP = 6** **CON = 7**	**EXP:** 82 ± 2.4 **CON:** 82.6 ± 6.9	Both	3 week/3 times completed Kinect training two Kinect games were used: Your Shape: Fitness Evolved and Kinect adventures	Normal activities	TUG
Chao, 2015	USA	***n*** **= 32** **EXP = 16** **CON = 16**	**EXP:** 86.63 (4.18) **CON:** 83.75 (8.04)	Both	4 week/2 times SAHA + Nintendo Wii fit	Health educational session	TUG, 6-MWT, FES
Cicek, 2020	Turkey	***n*** **= 20** **EXP = 16** **CON = 14**	**EXP:** 72.3 (5.9) **CON:** 73.9 (4.6)	Both	8 weeks/2 times. Nintendo Wii fit plus	Normal activities	TUG, QoL
Daniel, 2012	USA	***n*** **= 23** **EXP = 8** **CON = 7**	**EXP:** 80.00 (3.370) **CON:** 72.60 (4.60)	Both	15 week/3 times Nintendo Wii fit	Traditional senior fitness program	6-MWT, 8-FUG
Delbaere, 2021	Australia	***n*** **= 20** **EXP = 10** **CON = 10**	**EXP:** 86.9 ± 5.6 **CON:** 87.5 ± 6.6	Both	12 month/2 times Virtual reality dual-task training using the BioRescue	no additional training	TUG, FES
Duque, 2013	Australia	***n*** **= 70** **EXP = 40** **CON = 30**	**EXP:** 79.3 ± 10 **CON:** 75 ± 8	Female	6 week/2 times Attended balance training	-	FES
Eggenberger, 2015	Switzerland	***n*** **= 89** **EXP = 24** **CON = 22**	**EXP:** 77.30 (6.30) **CON:** 78.50 (5.10)	Female	24 week/2 times Virtual reality video-game dancing	Treadmill walking	Velocity, 6-MWT, FES

(continued)

Table 1. (continued)

		Participants			Intervention		
Author; year	Country	*N*	Age: Mean (SD)	Gender	Experimental group	Control group	Outcome measures
Eggenberger, 2016	USA	***n* = 42** **EXP =** 19 **CON =** 14	**EXP:** 72.8 (5.9) **CON:** 77.8 (7.4)	Both	8 week/3 times Interactive cognitive-motor video-game dancing	Balance and stretching training	FES-I
Fakhro, 2019	Switzerland	***n* = 64** **EXP =** 30 **CON =** 30	**Both:** 72.20 (5.20)	Female	8 week/3 times Soccer heading" and "Table Tilt"	Underwent no training	TUG
Fu, 2015	Australia	***n* = 64** **EXP =** 30 **CON =** 30	**EXP:** 82.4 (3.8) **CON**: 82.3 (4.3)	Both	6 weeks/3 times Balance training with Wii fit equipment	Conventional exercise	FES
Gomes, 2018	Brazil	***n* = 30** **EXP =** 15 **CON =** 15	**EXP:** 83 (5.87) **CON:** 85 (6.19)	Both	7 week/2 times participants played five of 10 selected games. Ten NWFP games were selected according to their cognitive	Received a booklet with information and illustrations outlining the benefits and risks of physical activity. The booklet was based on World health	FES-I
Gschwind, 2015	Australia	***n* = 148** **EXP =** 24 **CON =** 61	**EXP:** 80.10 (6.30) **CON:** 80.20 (6.50)	Female	16 week/2 times walking, stepping, weight shifting	-	TUG, QoL
Htut, 2018	Thailand	***n* = 84** **EXP =** 21 **CON =** 21	**EXP:** 75.8 ± 4.89 **CON:** 76.0 ± 5.22	Both	8 weeks/3 times Ten games from Xbox 360 (Flextronics, Wistron, Celestica, Foxconn) were chosen	Control group did not	TUG, FES
Jorgensen, 2013	Denmark	***n* = 58** **EXP =** 27 **CON =** 30	**EXP:** 75.90 (5.70) **CON:** 73.70 (6.10)	Female	10 week/2 times The participants could choose freely between five different balance exercises (table tilt, slalom ski, perfect 10, tight rope tension, penguin slide)	The participants in CON were instructed to wear the EVA insoles in their shoes every day for the entire duration of the trial	TUG, FES-I
Jung, 2015	Korea	***n* = 24** **EXP =** 8 **CON =** 8	**EXP:** 74.3 ± 2.1 **CON:** 73.6 ± 2.4	Female	8 week/2 times wakeboard, Frisbee dog, jet ski, and canoe games was used for the NWS group. Participants controlled a virtual character on the screen by swinging, rowing, or tilting remote controllers with motion	not performed an exercise program	TUG

(continued)

Table 1. (continued)

		Participants			Intervention		
Author; year	Country	N	Age: Mean (SD)	Gender	Experimental group	Control group	Outcome measures
Karahan, 2015	Turkey	***n* = 100** **EXP =** 48 **CON =** 42	**EXP:** 71.3 ± 6.1 **CON:** 71.5 ± 4.7	Both	6 week/5 times exergames using the Xbox KinectTM device	Home exercise	TUG
Keogh, 2014	New Zealand	***n* = 34** **EXP =** 19 **CON =** 15	**EXP:** 81.00 (7.00) **CON:** 85.00 (7.00)	Both	8 weeks Nintendo Wii Sports	Usual routine activities	QoL
Konstantinidis, 2014	Greece	***n* = 232** **EXP =** 116 **CON =** 116	**EXP:** 70.0 (6.2) **CON:**69.1 (6.6)	Both	8 week/5 times Used (FFA) exergaming platform System.	Followed cognitive training	QoL, 8-FUG
Lai, 2013	Taiwan	***n* = 30** **EXP =** 15 **CON =** 15	**EXP:** 70.6 (3.5) **CON:** 74.8 (4.7)	Both	6 week/3 times Interactive video-game-based (IVGB)	Received no intervention	MFES, TUG
Lauzé, 2018	Canada	***n* = 32** **EXP =** 21 **CON =** 11	**EXP:** 80.1 (7.5) **CON:**83.2 (6.7)	Both	12 week/2 times 7 aerobic exercises, 8 resistance and balance exercises, and a cool-down period	Did not receive any materials	TUG, QoL, speed
Lazar, 2023	India	***n* = 44** **EXP =** 22 **CON =** 22	**EXP:** 69.44 (6.66) **CON:** 66.33 (6.51)	Both	4 week/3 times IVR training group with oculus quest 2 device	Conventional balance training	FES, TUG
Lee, 2014	USA	***n* = 82** **EXP =** 40 **CON =** 42	**Both:** 75.20 (6.60)	Both	10 week/3 times Station with boxing, tennis, and bowling and the other station with table tilt, slalom ski, perfect 10, penguin slide, tight rope, and obstacle course games	Walk, strengthening exercises balancing activities	Velocity, cadence
Lee, 2015	Korea	***n* = 54** **EXP =** 26 **CON =** 28	**EXP:** 68.8 (4.6) **CON:** 67.7 (4.3)	Female	8 weeks/3 times All subjects in the virtual reality group attended all virtual reality-based exercise sessions at the university research laboratory	Their exercise program consisted of postural, balance, functional, lower body coordination, and lower body strength exercises	8-FUG, QoL
Lee, 2017	Korea	***n* = 44** **EXP =** 21 **CON =** 19	**EXP:** 76.15 ± 4.55 **CON:** 75.71 ± 4.91	Both	6 week/2 times When a participant stands on the balance board, which is a pressure sensor, an avatar appears on the monitor and replicates the participant's movements, providing visual and auditory feedback	-	TUG

(continued)

Table 1. (continued)

		Participants			Intervention		
Author; year	Country	*N*	Age: Mean (SD)	Gender	Experimental group	Control group	Outcome measures
Lee, 2020	Korea	***n* = 56** **EXP =** 28 **CON =** 28	**EXP:** 81.01 ± 6.89 **CON:** 79.47 ± 6.15	Both	4 week/5 times non-motorized treadmill	Non-motorized treadmill gait training without virtual reality	TUG, Velocity, cadence
Lyubenova, 2023	Bulgaria	***n* = 50** **EXP =** 24 **CON =** 26	-	Female	7 week/3 times PT combined with video-game VRG	PT	Cadence, gait speed
Maillot, 2012	France	***n* = 32** **EXP =** 16 **CON =** 16	**EXP:** 73.47 (4.10) **CON:** 73.47 (3.00)	Both	14 weeks/2 times Nintendo Wii Sports	Without intervention	8-FUG, 6-MWT
Maillot, 2014	France	***n* = 16** **EXP = 8** **CON =** 8	**EXP:** 74.1 (4.7) **CON:** 74.0 (2.1)	Both	12 week/2 times Wii tennis, boxing game, balance board, soccer headers, ski jump hula hoop, marbles games and tennis, and boxing games	Received no intervention	QoL, 8-FUG, 6-MWT
Merriman, 2015	Ireland	***n* = 76** **EXP =** 38 **CON =** 38	**EXP:** **F:** 74.1 (6.7) **H:** 74.9 (9.0) **CON:** **F:** 73.4 (7.0) **H:** 74.3 (11.1)	Both	5 weeks/2 times VR display in which the on-screen position of a target object was controlled by shifts in postural balance on a Wii balance board	Passive control condition	FES
Nicholson, 2015	Australia	***n* = 41** **EXP =** 19 **CON =** 22	**EXP:** 75.1 (5.8) **CON:** 73.9 (5.1)	Both	6 week/3 times Nintendo Wii Fit	Without intervention	TUG, FES, speed
Orsega-smith, 2012	USA	***n* = 25** **EXP =** 16 **CON =** 9	**EXP:** 72.0 (8.5) **CON:** 70.6 (4.9)	Both	4–8 weeks/2 times Nintendo Wii Fit: Balance and yoga)	Without intervention	TUG
Padala, 2012	USA	***n* = 22** **EXP =** 11 **CON =** 11	**EXP:** 79.3 (3.8) **CON:** 81.6 (5.2)	Both	8 week/5 times (single leg extensions, lunges, and torso twists). (Half-moon, warrior pose, chair, and sun salutation). (Ski slalom, ski jump, table tilt, and penguin slide)	Walking program indoors, 30 min daily, walking to and from the starting point as warming up and cooling down. Walking at own pace	QoL, TUG
Park, 2015	Korea	***n* = 30** **EXP =** 15 **CON =** 15	**EXP:** 66.5 (8.1) **CON:** 65.2 (7.9)	Both	8 week/3 times ball exercise with virtual reality exercise	ball exercise as a general exercise	TUG

(continued)

Table 1. (continued)

		Participants			Intervention		
Author; year	Country	*N*	Age: Mean (SD)	Gender	Experimental group	Control group	Outcome measures
Peng, 2020	Taiwan	***n*** **=** 110 **EXP =** 56 **CON =** 54	**EXP:** 70.7 (4.6) **CON:** 72.0 (5.7)	Both	12 week/1 times ladder-type, three-by-three grid-type, and circle-type mat exergames with simultaneous cognitive–physical training (EMAT)	Control group underwent a multicomponent exercise intervention focused on physical and cognitive training	FES
Phirom, 2020	Thailand	***n*** **=** 40 **EXP =** 20 **CON =** 20	**EXP:** 70.2 (4.2) **CON:** 69.4 (3.4)	Both	12 week/3 times interactive physical-cognitive game-based training program	Received educational material covering cognitive enhancement and fall prevention strategies	TUG
Pichierr, 2012	Switzerland	***n*** **=** 31 **EXP =** 11 **CON =** 10	**EXP:** 86.9 (5.1) **CON:** 85.6 (4.2)	Both	12 week/2 times DDR Stepmania	Physical exercise program	Velocity, cadence
Pluchino, 2012	USA	***n*** **=** 80 **EXP =** 12 **CON =** 14	**EXP:** 70.7 (8.5) **CON:** 76.0 (7.7)	Both	8 week/2 times vieo game balance board program	Standard balance exercise program	TUG
Queiroz, 2017	Brazil	***n*** **=** 27 **EXP =** 13 **CON =** 14	**EXP:** 60.7 (3.6) **CON:** 59.8 (4.1)	Both	12 week/3 times athletics, bowling, boxing, skiing, soccer, tennis, and table tennis	Aerobic exercises Activities with the ergometers	TUG
Ray, 2012	USA	***n*** **=** 87 **EXP =** 29 **CON =** 40	-	Both	15 week/3 times playing the Wii bowling or Wii boxing games. The Wii Fit Plus balance board	Various traditional senior fitness programs, including a rigorous seated aerobics program	6-MWT, 8-FUG
Rendon, 2012	USA	***n*** **=** 40 **EXP =** 16 **CON =** 18	**EXP:** 85.7 (4.3) **CON:** 83.3 (6.2)	NR	18 week/3 times Nintendo Wii Fit	Without intervention	8-FUG
Rica, 2020	Brazil	***n*** **=** 50 **EXP =** 34 **CON =** 16	>60	Female	12 weeks/3 times Kinect-based exercise protocol	Played board games and were encouraged to continue their normal daily activities.	QoL, 8-FUG
Sa´pi, 2019	Hungary	***n*** **=** 75 **EXP =** 30 **CON =** 22	**EXP:** 69.57 – 4.66 **CON:** 67.18 – 5.56	Both	6 week/3 times practiced Kinect adventures and Sports	No intervention control	Velocity
Sato, 2015	Japan	***n*** **=** 57 **EXP =** 28 **CON =** 26	**EXP:** 70.1 (5.4) **CON:** 68.5 (5.5)	Both	12 weeks/2–3 times The intervention game content used Kinect and Kinect SDK version	-	Velocity, cadence

(continued)

Table 1. (continued)

Author; year	Country	Participants: *N*	Participants: Age: Mean (SD)	Participants: Gender	Intervention: Experimental group	Intervention: Control group	Outcome measures
Schattin, 2016	Switzerland	***n* = 27** **EXP =** 13 **CON =** 14	**EXP:** 78.7 (8.3) **CON:** 78.0 (7.8)	Both	8–10 week/3 times Exergame training	Balance training	Cadence, speed
Schoene, 2013	Australia	***n* = 37** **EXP =** 15 **CON =** 17	**EXP:** 77.5 (4.5) **CON:** 78.4 (4.5)	NR	8 week/2 times Exergame DDR Stepmania	Usual routine activities	TUG, FES
Schwenk, 2014	USA	***n* = 33** **EXP =** 17 **CON =** 16	**EXP:** 84.3 (7.3) **CON:** 84.9 (6.6)	Both	4 week/2 times balance training including weight shifting and virtual obstacle crossing tasks with visual/ auditory real-time joint movement feedback using wearable sensors	No intervention	TUG, speed
Singh, 2013	Malaysia	***n* = 38** **EXP =** 18 **CON =** 18	**EXP:** 61.1 (3.7) **CON:** 64.0 (5.9)	Female	6 weeks/2 times Wii Balance Board	Traditional senior fitness balance program	TUG
Stanmore, 2019	United Kingdom	***n*** = 92 **EXP =** 49 **CON** = 43	**EXP:** 77.9 (8.9) **CON:** 77.8 (10.2)	Both	12 week/3 times the same standard care as the control group was given. In addition, exergames were offered (under the supervision of a physiotherapist or physiotherapist assistant) in the assisted living facility rooms	Control participants were encouraged to do three preselected (by the physiotherapist) exercises from the OTAGO list over	TUG, FES, QoL
Tsang and Fu, 2016	Hong Kong	***n* = 79** **EXP =** 39 **CON =** 40	**EXP:** 82.3 (3.8) **CON:** 82.0 (4.3)	Both	6 week/3 times The Wii Fit balance training games included soccer heading, table tilt, and balance bubble	Leg strengthening exercises, tandem standing exercise in parallel bars, tandem walking in parallel bars, sideways walking and turning around in parallel bars, stepping exercises, sit-to-stand exercises, and mini-squats	TUG
Yang, 2020	Taiwan	***n* = 20** **EXP =** 10 **CON =** 10	**EXP:** 68.71 (64.09–74.84) **CON:** 67.54 (62.08–76.75)	Both	5 week/2 times Kinect exercise	Conventional exercise over balance training	TUG
Yesilyapark, 2016	Turkey	***n* = 18** **EXP =** 7 **CON =** 11	**EXP:** 70.1 (4.0) **CON:** 73.1 (4.5)	Both	6 week/3 times VR-based balance exercises	Conventional balance exercises	TUG, FES

(continued)

Table 1. (continued)

		Participants			Intervention		
Author; year	Country	*N*	Age: Mean (SD)	Gender	Experimental group	Control group	Outcome measures
Yousefi Babadi and Daneshmandi, 2021	Iran	***n*** **= 36** **EXP =** 12 **CON =** 12	**EXP:** 66.5 (3.8) **CON:** 66.7 (3.2)	Both	9 week/3 times virtual reality training	Conventional balance training	TUG
Zahedian-Nasab, 2021	Iran	***n*** **= 60** **EXP =** 30 **CON =** 30	**EXP:** 69.7 (7.7) **CON:** 72.0 (7.8)	Both	6 week/2 times VR exercises based on Xbox Kinect	Routine exercises	TUG, FES

A meta-analysis of five trials (364 participants) demonstrated a statistically significant improvement in social relationship scores with VR (MD = 0.31, 95% CI: 0.10 to 0.52; p = 0.004), with moderate heterogeneity (I^2 = 70%; Figure 4B).

A meta-analysis of three trials with 296 participants revealed a statistically significant improvement in physical health scores with VR, as revealed in Figure 4C (MD = 0.31, 95% CI: 0.08 to 0.54; p = 0.009), with no heterogeneity (I^2 = 0%).

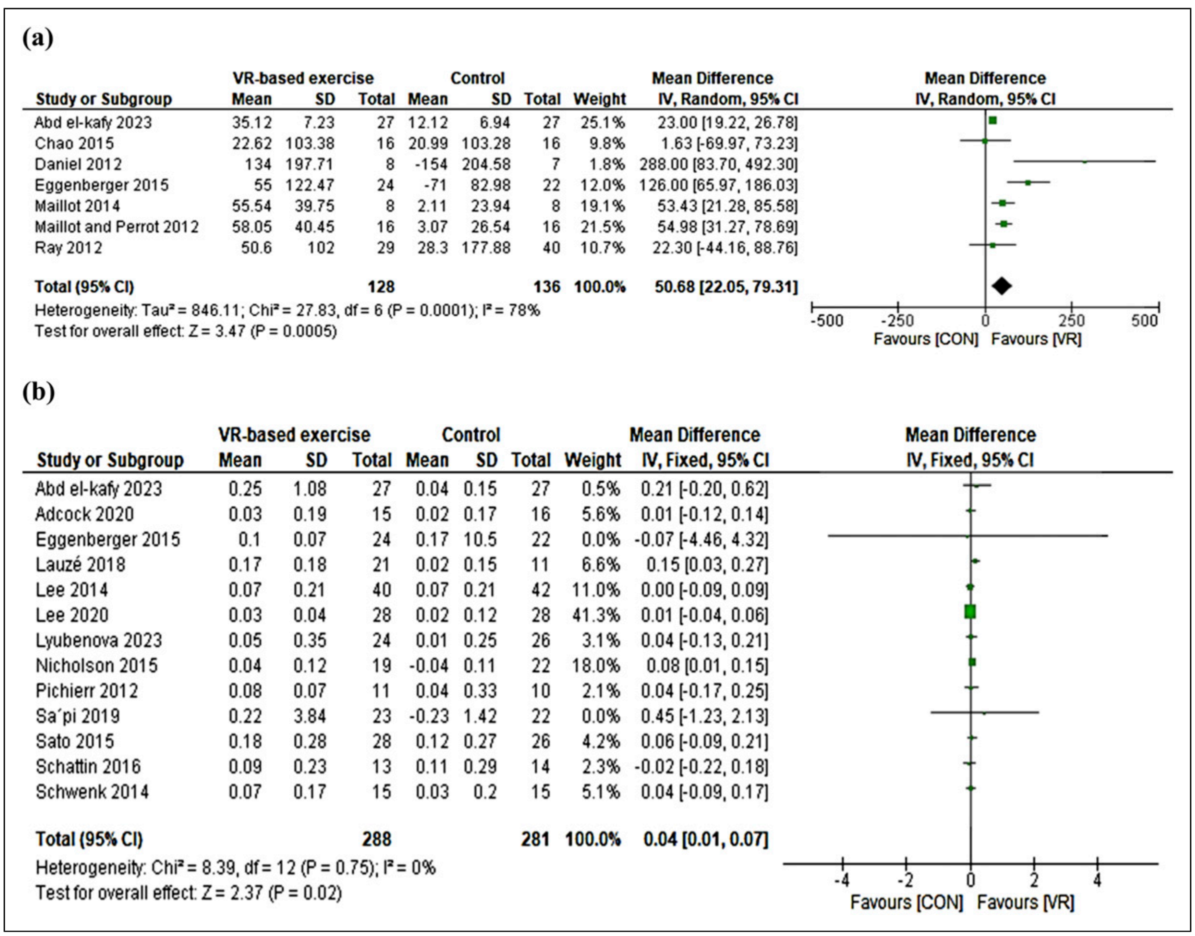

Figure 2. Effect of VR-based exercise interventions on (A) 6-MWD and (B) gait speed.

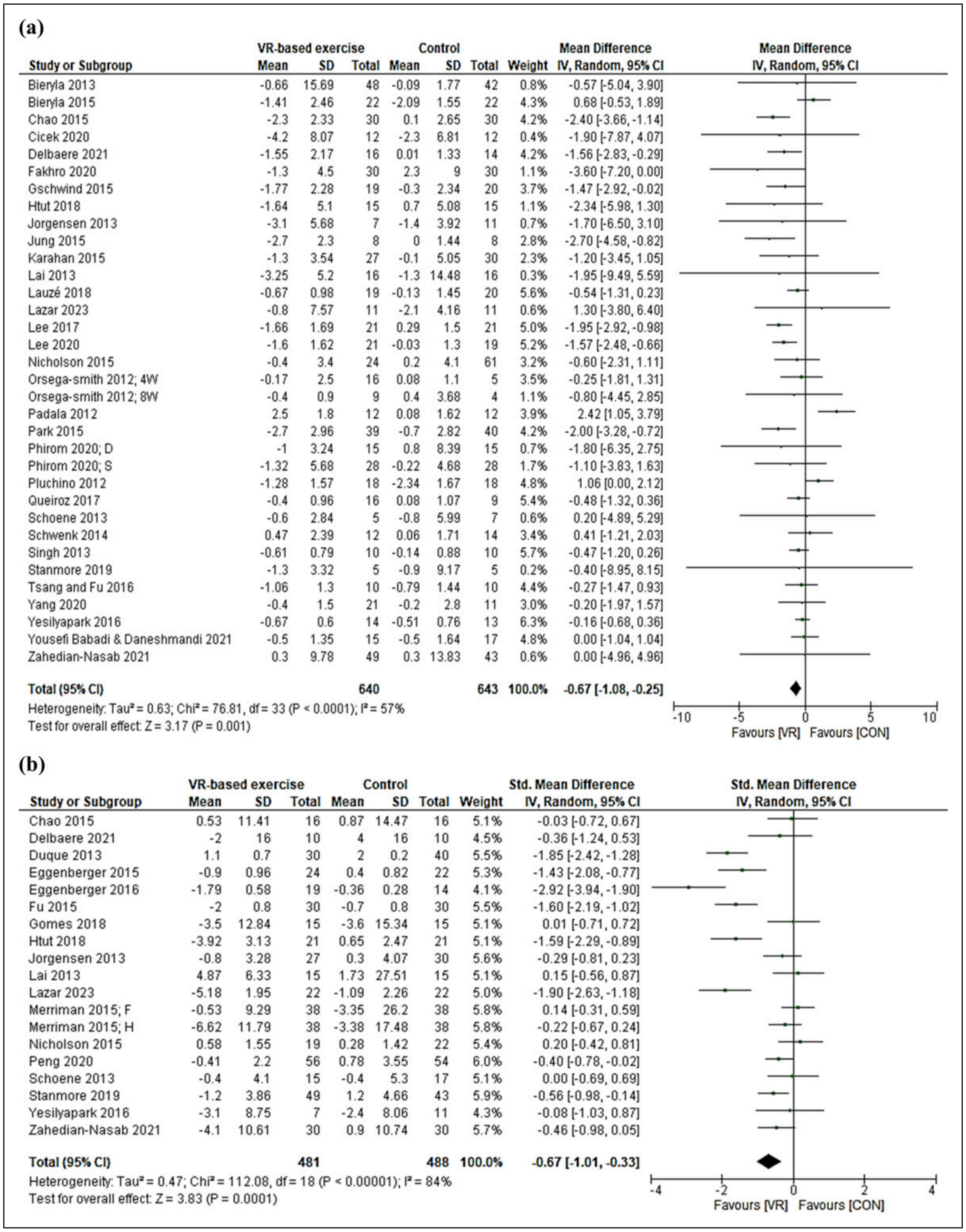

Figure 3. Effect of VR-based exercise interventions on (A) TUG and (B) FES.

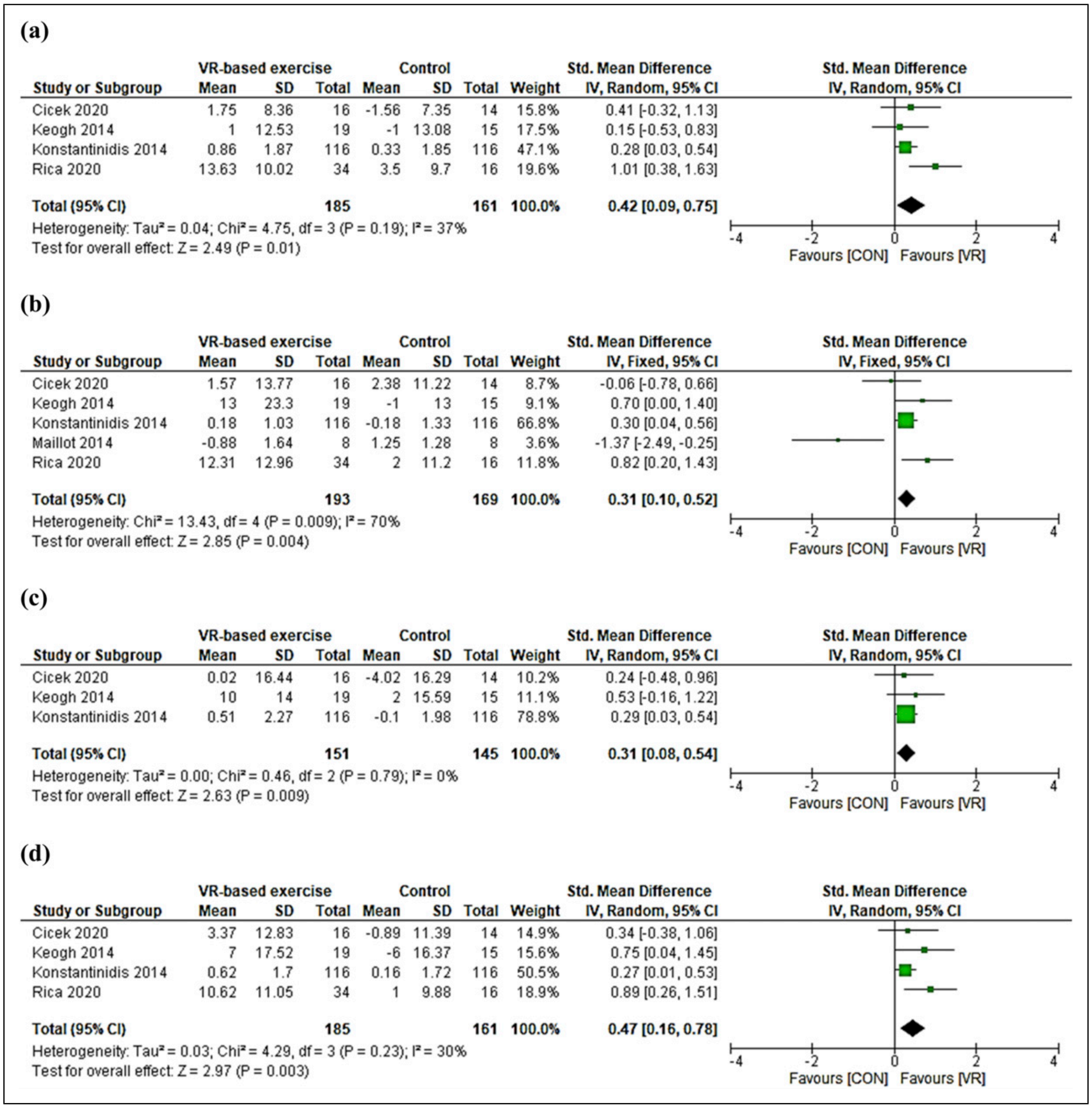

Figure 4. Effect of VR-based exercise interventions on quality of life including (A) environmental health, (B) social relation, (C) physical health, and (D) psychological health scores.

A meta-analysis of four trials (346 participants) showed a significant improvement in psychological health scores with VR (MD = 0.47, 95% CI: 0.16 to 0.78; $p = 0.003$), with low heterogeneity ($I^2 = 30\%$; Figure 4D).

Study Quality and Publication Bias

The median TESTEX score was 10 (see Supplemental Table S14). Notably, none of the studies monitored activity in the control group. Thirteen studies conducted intention-to-treat analyses, 27 reported allocation concealment, and 50 provided randomization details. Blinded assessors were employed in 23 studies. However, none of the studies reported exercise volume, energy expenditure, point measures with variability, eligibility criteria, baseline group similarity, or relative exercise intensity.

Funnel plot analyses did not indicate any evidence of publication bias (Supplemental Figures S4-6), suggesting that the pooled results were robust and reliable.

Risk of Bias Assessment

The risk of bias across the 56 included trials was assessed using the Cochrane RoB 2 tool. None of the studies were rated as having a low overall risk of bias; 60.72% were judged to have “some concerns,” while 39.28% were classified as high

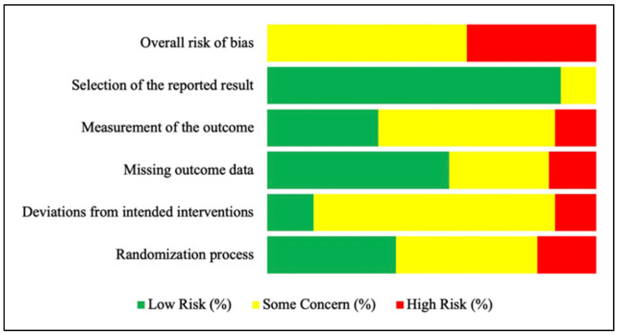

Figure 5. The risk of bias results for each domain.

risk. In the domain of the randomization process, 39.29% of studies were rated as low risk, 42.85% as having some concerns, and 17.86% as high risk. Deviations from intended interventions presented the highest concern, with only 14.29% of studies rated as low risk and 73.21% rated as having some concerns. With regard to missing outcome data, 55.35% of studies were considered low risk, 30.36% had some concerns, and 14.29% were high risk. For measurement of the outcome, 33.93% were rated low risk, 53.57% had some concerns, and 12.5% were high risk. Notably, the risk of bias due to selective reporting was minimal, with 89.29% of studies rated low risk and none rated high risk (Supplemental Table S15 and Figure 5).

Discussion

This systematic review and meta-analysis examined the effects of VR-based exercise training on walking capacity, fall risk, and quality of life in healthy older adults. The findings reveal that VR-based exercise significantly enhanced walking capacity (notably 6-MWD and gait speed), reduced fall risk (via TUG times and FES scores), and improved quality-of-life domains, including environmental health, social relations, and physical health. These results underscore VR-based exercise as a promising, technology-driven intervention to support functional independence and well-being in older adults, with potential applications in clinical practice and community settings. In support of these findings, the current review incorporated a detailed risk of bias assessment, which revealed that while most studies had some concerns, a substantial proportion were rated as high risk overall, highlighting the need for cautious interpretation of the pooled results.

An important practical advantage of VR-based exercise is its immersive and gamified nature, which may enhance motivation, engagement, and adherence among older adults. Gamification elements such as real-time feedback, task progression, and interactive environments can reduce boredom and increase enjoyment, thereby supporting long-term participation—an essential factor in achieving sustained health benefits (H. S. Lee et al., 2019).

VR-based exercise significantly improved 6-MWD and gait speed, consistent with prior studies highlighting VR's role in enhancing physical function (Lamoth et al., 2011). Lamoth et al. (2011) attributed these gains to VR's immersive environments, which facilitate motor learning and rehabilitation. However, high heterogeneity in 6-MWD outcomes ($I^2 = 78\%$) suggests variability in treatment effects, likely due to differences in VR program design, intensity, or duration. This variability signals a critical need for standardized protocols to optimize VR's impact on endurance and walking efficiency—key factors in maintaining older adults' independence in daily activities. In contrast, gait speed improvements showed low heterogeneity, indicating a robust, consistent effect across studies. Sensitivity analyses identified influential studies, reinforcing the importance of program-specific features. These findings align with Suleiman-Martos et al. (2022), who reported significant mobility gains from VR-based challenges (Suleiman-Martos et al., 2022). Clinicians and program developers could leverage these insights to design VR interventions that enhance walking capacity, supporting older adults' ability to remain active and engaged in their communities (Schoene et al., 2013).

VR-based exercise reduced fall risk, with significant improvements in TUG (effect size = −0.67) and FES scores, though no notable effect was observed for 8-FUG times. The TUG improvement reflects enhanced functional mobility, a critical determinant of fall prevention, despite moderate heterogeneity suggesting variability in intervention protocols or participant profiles. For FES, high heterogeneity indicates that VR's effect on fear of falling varies with program features and psychological engagement. These findings position VR as a practical tool for improving balance and confidence, offering a safe, controlled setting to practice real-world tasks—a key advantage for older adults at risk of falls (Levin et al., 2015). The non-significant 8-FUG results and its heterogeneity highlight areas for refinement. Mirelman et al. (2016) demonstrated that VR-based treadmill training reduced fall rates, suggesting that task complexity and system engagement are pivotal (Mirelman et al., 2016). Future efforts to standardize VR protocols could enhance their efficacy in fall prevention programs, benefiting both individual older adults and healthcare systems by reducing fall-related injuries.

VR-based exercise improved specific quality-of-life domains—environmental health, social relations, psychological health, and physical health—but showed no significant effect on overall SF-36 scores, suggesting domain-specific rather than global benefits. The enhancement in environmental health likely stems from VR's ability to simulate enriching, interactive settings, fostering connectedness, and reducing isolation—a critical consideration for older adults in care or community settings (Montana et al., 2020). Improvements in social relations and physical/psychological health further highlight VR's potential to promote holistic well-being (Cikajlo et al., 2012). Low heterogeneity in these analyses indicates consistent positive effects, reinforcing VR's reliability as an intervention. These findings suggest that VR could be integrated into wellness programs to enhance older adults' quality of life, though tailoring content to address broader domains may amplify its impact.

Compared to studies in clinical populations—such as stroke or Parkinson's disease—this review demonstrates that VR-based interventions can offer substantial benefits even in healthy older adults. While previous work in clinical groups often focuses on rehabilitation or motor recovery, our findings reinforce VR's role in preserving functional capacity and preventing decline in non-clinical, aging populations (Brunner et al., 2017). This emphasizes VR's utility as a preventive rather than rehabilitative tool in the context of healthy aging.

The lack of a significant overall SF-36 effect, despite its common use as a quality-of-life measure, may stem from its broad scope, encompassing eight subscales (e.g., physical functioning, vitality, and role limitations) not uniformly sensitive to VR's physical focus. Domains such as role limitations-emotional or general health may be less responsive than physical or social functioning, attenuating overall score changes. Moreover, the brief duration of VR interventions (6–12 weeks) may limit global quality-of-life shifts, especially in healthy older adults with high baseline scores.

Limitations

Despite these promising results, limitations warrant consideration. High heterogeneity in 6-MWD, FES, and 8-FUG analyses reflects variability in intervention protocols, durations, and VR features, potentially limiting generalizability. The absence of a significant SF-36 improvement further suggests that current VR programs may require adaptation to address all quality-of-life facets comprehensively, particularly less responsive subscales like bodily pain or role-emotional. Additionally, the included studies employed heterogeneous control conditions, ranging from passive (e.g., no intervention) to active (e.g., conventional exercise or physical therapy), which may have contributed to differences in observed effect sizes and limits comparability across studies.

Moreover, although most trials were rated as having some concerns in the risk of bias assessment, nearly 40% were judged to be at high risk, particularly regarding deviations from intended interventions and outcome measurement. This methodological variability may have influenced effect estimates and should be considered when interpreting the strength of the evidence.

While subgroup stratification was not feasible due to insufficient reporting and inconsistent comparator definitions, this limitation has been acknowledged, and future meta-analyses are recommended to explore stratified comparisons to better isolate the specific effects of VR-based interventions. Future research should prioritize developing standardized, evidence-based VR protocols—specifying session length, frequency, and immersive elements—to maximize benefits across diverse older adult populations. Additionally, examining subscale-specific SF-36 outcomes in larger, longer-term trials could clarify VR's full potential and guide the design of interventions targeting both physical and psychosocial well-being. Exploring optimal training conditions and long-term effects could further solidify VR's role in healthy aging strategies.

Conclusion

This systematic review and meta-analysis demonstrate that VR-based exercise significantly enhances walking capacity, reduces fall risk, and improves specific quality-of-life domains in healthy older adults. Notable impacts on 6-MWD, gait speed, TUG, FES, and domains like environmental and physical health position VR as an innovative, effective intervention for promoting functional independence and well-being. These findings offer actionable insights for clinicians, caregivers, and policymakers seeking to integrate VR into preventive health and community programs for older adults. However, variability in intervention effects underscores the need for standardized protocols and further research to optimize VR's potential across diverse settings and populations. Importantly, the scalability of VR—especially through home-based systems and mobile platforms—supports its broader adoption in aging-in-place initiatives and community-based health promotion.

Implications and Recommendations for Practice

The findings of this systematic review and meta-analysis highlight VR-based exercise as an effective intervention for enhancing walking capacity, reducing fall risk, and improving specific quality-of-life domains in healthy older adults. These results have several implications for practice. Clinicians and community health providers can integrate VR interventions to improve gait speed, endurance (e.g., 6-MWD), and functional mobility (e.g., TUG), supporting older adults' independence and reducing fall-related injuries. The consistent benefits in social functioning, vitality, and environmental mastery suggest that VR programs could be incorporated into wellness initiatives to foster social engagement and well-being, particularly for those at risk of isolation.

However, the variability in intervention effects and the lack of a significant overall SF-36 impact underscore the need for tailored approaches. Practitioners should prioritize VR protocols with standardized durations (e.g., 8–12 weeks), frequencies (e.g., 2–3 sessions weekly), and immersive features proven to optimize physical outcomes, as suggested by low heterogeneity findings for gait speed. To address the nuanced SF-36 subscale results, programs could be adapted to target broader domains—such as incorporating cognitive challenges or emotional support elements—to enhance vitality and role functioning beyond physical health. For fall prevention, VR systems should emphasize balance-focused tasks and real-world simulations, building on evidence of TUG and FES improvements. These adaptations could maximize VR's potential as a scalable tool for healthy aging.

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Data Availability Statement

The data supporting this study's findings are available upon request from the corresponding author.

Supplemental Material

Supplemental material for this article is available online.

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