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Title: The Effect of Virtual Reality Exercise on Bone Mineral Density in Adults: A Systematic Review and Meta-Analysis

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To appear in: ***Physical Treatments***

Received date: 2026/01/28

Revised date: 2026/06/06

Accepted date: 2026/06/11

First Online Published: 2026/06/23

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Please cite this article as:

Bahrami P, Ashoury H. The Effect of Virtual Reality Exercise on Bone Mineral Density in Adults: A Systematic Review and Meta-Analysis. ***Physical Treatments.*** Forthcoming 2026. DOI: http://dx.doi.org/10.32598/ptj.2026.813.1

DOI: http://dx.doi.org/10.32598/ptj.2026.813.1

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Abstract

Purpose: Virtual Reality (VR) has emerged as a novel, engaging tool to overcome adherence challenges in bone-strengthening exercise. This systematic review and meta-analysis aims to quantitatively synthesize the evidence on the impact of VR-based interventions on Bone Mineral Density (BMD) in adults.

Methods: We performed a systematic literature search in line with PRISMA guidelines using PubMed, Scopus, and Web of Science for studies published between 2000 and 2024. Eligible studies included randomized controlled trials (RCTs) and non-randomized controlled trials that had a concurrent control group and examined the effect of VR-based exercise on BMD outcomes in adults in comparison with a control or alternative intervention. Quasi-experimental trials lacking a parallel control group (for example, single-arm pre-post designs) were omitted because of their high bias risk and the impossibility of deriving comparative effect estimates for the meta-analysis. The Cochrane RoB 2 tool (version 2) was employed to evaluate the risk of bias. This instrument assesses five areas: the randomization procedure, deviations from intended interventions, completeness of outcome data, outcome measurement, and selection of reported findings. Each domain received a judgment of either "low risk," "some concerns," or "high risk." Two examiners independently appraised every trial, and any disagreements were settled through discussion.

Results: After an initial retrieval of 1,248 publications and following a thorough filtering and reassessment process, 10 randomized controlled trials (RCTs) fulfilled the predefined inclusion criteria. The overall mean difference (MD) for BMD change was 0.028 g/cm² (95% CI: 0.018 to 0.038), which translates into a relative rise of roughly 2-3% — a magnitude comparable to that seen in earlier exercise-based investigations. A subgroup analysis based on methodological quality revealed a larger effect among high-quality studies (PEDro score ≥ 8), where the standardized mean difference (SMD) was 0.95 (95% CI: 0.70–1.20; $p < 0.001$; $I^2 = 28.1\%$). In contrast, moderate-quality trials (PEDro score 5-7) yielded an SMD of 0.65 (95% CI: 0.40–0.90; $p < 0.001$; $I^2 = 29.7\%$). Significant benefits were also observed for secondary endpoints: a 25% average decrease in fall risk (95% CI: 18–32%; $I^2 = 30.5\%$) and a 20% average enhancement in balance scores (95% CI: 14–26%; $I^2 = 27.9\%$). Collectively, these findings indicate that exercise performed via VR is a beneficial intervention for increasing BMD and improving associated functional capabilities in adult populations.

Conclusion: Synthesized evidence confirms that VR exercises are an effective intervention for significantly improving BMD in adults, offering a promising, engaging strategy for osteoporosis prevention. These pooled results provide a robust, quantitative estimate of efficacy to guide clinical and public health practice. Future research should prioritize long-term adherence and comparative effectiveness.

Keywords: Virtual Reality, Bone Mineral Density, Meta-Analysis, Osteoporosis, Exercise.

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Highlights

1- A systematic review and meta-analysis confirm Virtual Reality (VR) exercise significantly improves Bone Mineral Density (BMD) in adults.
2- Pooled quantitative data shows a clinically meaningful positive effect on BMD, alongside significant improvements in balance.
3- VR presents an effective and engaging alternative for osteoporosis prevention, though long-term adherence and effects warrant further study.

Plain Language Summary

This research combined data from multiple studies to evaluate whether Virtual Reality (VR) "game-like" workouts can strengthen bones to help prevent osteoporosis. The analysis confirms that VR exercise is an effective and enjoyable alternative to traditional workouts that people can find hard to stick with. The combined results show that VR significantly improves bone strength and balance, making it a promising new tool for bone health, though more research is needed on its long-term use and how to keep people engaged.

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1. Introduction

Bone mineral density (BMD) serves as a crucial determinant of bone health and a key predictor of osteoporosis and associated fracture risk (1, 2). Osteoporosis affects approximately 200 million people worldwide, with an estimated 8.9 million fragility fractures occurring annually – equivalent to one osteoporotic fracture every three seconds (3). The lifetime risk of an osteoporotic fracture is 30–40% in women and 15–20% in men over the age of 50 (4). In the European Union, the annual healthcare cost of osteoporotic fractures exceeds €37 billion, while in the United States, costs approach $74 billion per year (2, 5, 6). Affecting millions worldwide, it poses a significant public health burden, particularly among postmenopausal women and older adults, resulting in serious morbidity and substantial healthcare costs (7, 8). Conventional interventions to improve BMD typically involve resistance and weight-bearing exercises, which have demonstrated efficacy in enhancing bone strength and mitigating fracture risk (9, 10). However, adherence to such exercise regimens is often suboptimal due to various factors, including lack of motivation, accessibility issues, and the perceived monotony of traditional training programs (11, 12). This adherence challenge represents a significant barrier to effective osteoporosis prevention and management strategies (2, 10-12).

Exercise delivered via virtual reality (VR) has emerged as an innovative approach . VR-facilitated exercise offers a promising avenue. The immersive nature of VR can foster a sense of presence and competition, thereby enhancing adherence to physical activity programs. It is important to clarify that VR is a delivery method; the active therapeutic agent is the exercise performed within the VR environment (13, 14). By providing immersive and engaging environments, this technology has shown considerable potential to enhance motivation and enjoyment during exercise (15, 16). This is particularly relevant for older adult populations, who may disengage from physical activity due to mobility limitations, lack of motivation, or the repetitive nature of conventional exercises (2, 6, 17). Throughout this manuscript, the term "VR exercise" refers to physical exercise (e.g., balance training, resistance activities, aerobic movements) performed while immersed in a virtual reality environment (18). VR is conceptualized as a delivery method a platform that facilitates exercise engagement through immersion, interactivity, and real-time feedback (19). The active therapeutic agent remains the exercise (mechanical loading of bone), not the VR technology itself (20). This distinction is critical for interpreting the mechanisms and effects reported in this review. Given that mechanical loading through regular physical activity is a primary stimulus for bone remodeling and maintenance of BMD (2, 5, 10), VR offers a promising avenue to deliver and sustain the necessary osteogenic stimuli (18, 21). Through interactive and stimulating experiences such as performing exercises in simulated environments that are simultaneously entertaining and challenging VR can foster a sense of presence and competition, thereby directly influencing adherence to physical activity programs (6, 18, 22). Numerous studies indicate that VR-based interventions can effectively stimulate physical activity levels and improve intermediate health outcomes across diverse populations (6, 23, 24). For instance, Nambi et al. (2020) demonstrated that exercise performed within a VR environment can enhance muscular strength, improve balance, and reduce fall risk (22). The VR platform facilitates adherence by providing engaging, interactive, and motivating exercise experiences, but the physiological benefits are attributable to the physical activity (i.e., the mechanical loading of bones), not to the VR technology per se (22, 25). While these factors are closely related to fracture risk, they are surrogate markers; the direct osteogenic effect of VR-induced activity on bone itself remains less clear. Despite growing interest in the application of VR to promote physical activity, a focused synthesis of evidence regarding its direct impact on bone mineral density (BMD) in adults is lacking (18, 21, 22). To address this gap, we conducted a systematic review and meta-analysis to quantitatively synthesize evidence on VR exercise and BMD in adults. While preliminary evidence supports VR for enhancing physical activity(15, 21, 22), a pooled effect size for bone health outcomes is lacking. Therefore, the primary objective was to evaluate and statistically pool existing RCTs and clinical studies on VR-based exercise interventions for BMD in adults, thereby providing a robust effect size to inform clinical practice and public health initiatives. The findings may serve as a valuable resource for rehabilitation specialists, exercise practitioners, and health policymakers, aiding in the design of more effective, engaging, and evidence-based strategies to enhance bone health and prevent osteoporosis in aging populations. Ultimately, this review endeavors to contribute to the development of innovative, quantitatively supported approaches for optimizing bone health through emerging technologies.

Methods

The current systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (26). The protocol of this review was recorded in the

PROSPERO database (International Prospective Register of Systematic Reviews) and assigned a registration number [CRD420251274150].

2.1. Statistical Analysis

A systematic literature search was performed across eight electronic databases: PubMed, Scopus, Web of Science, SPORTDiscus, CINAHL, ScienceDirect, Embase, and the Cochrane Library (including Cochrane Central Register of Controlled Trials), covering the period from January 1, 2000 to June 30, 2024. The search strategy combined Medical Subject Headings (MeSH) and free-text keywords structured around the PICO framework as follows: Population terms included "Adult," "Aged," "Middle Aged," "Older Adults"; Intervention terms included "Virtual Reality," "VR," "Exergame," "Video Game," "Gamif*," "Immersive," "Head-Mounted Display"; and Outcome terms included "Bone Mineral Density," "BMD," "Bone Density," "DXA," "DEXA," "Osteoporosis," "Bone Health." The search was restricted to studies involving human adults (≥18 years) and published in the English language. The complete search strings adapted for each database are provided in Supplementary Appendix A. To ensure literature saturation, a supplementary search was conducted by screening reference lists of included studies and relevant reviews, as well as searching Google Scholar for grey literature (first 200 records). The study selection process is summarized in the PRISMA flow diagram (Figure 1). All statistical analyses were performed using RevMan (version 5.4). The primary outcome was the mean change in BMD (g/cm^2) from baseline to post-intervention, measured by DXA at the lumbar spine and femoral neck. Where studies reported both change scores and post-intervention values, change scores were prioritized for consistency with the random-effects model. Treatment effect was expressed as the mean difference (MD) with 95% confidence interval (CI), as BMD is measured on the same scale (g/cm^2) across studies. If standard deviation (SD) of the change score was not reported, it was imputed using the formula: $\text{SD change} = \sqrt{}\,(\text{SD\_baseline}^2 + \text{SD\_follow-up}^2 - 2 \times r \times \text{SD\_baseline} \times \text{SD\_follow-up})$.

A correlation coefficient of $r = 0.80$ was assumed based on similar bone health meta-analyses. To address expected clinical and methodological variability, a random-effects model (DerSimonian-Laird method) was employed. The degree of heterogeneity was quantified using the I^2 statistic, where values of 25%, 50%, and 75% correspond to low, moderate, and high heterogeneity, respectively. Pre-planned subgroup analyses were conducted by population (postmenopausal women vs. older adults), intervention duration (<6 vs. ≥6 months), and VR type (immersive vs. non-immersive). Sensitivity analyses were performed by excluding low-quality studies (PEDro score < 6). Publication bias was assessed visually using funnel plots. Although Egger's regression test was considered in the protocol, it was not performed because with only 10 included studies, the test has insufficient statistical power (reliable results typically require ≥15 studies). Therefore, funnel plot asymmetry was interpreted descriptively.

2.2. Eligibility Criteria

Following the PRISMA 2020 statement, a comprehensive search of the scientific literature was carried out using six bibliographic databases: PubMed, Scopus, Web of Science, SPORTDiscus, CINAHL, and ScienceDirect covering the period from January 1, 2000 to June 30, 2024, using the following Boolean search strategy combining MeSH terms and free-text keywords based on the PICO framework: ("Virtual Reality" OR "VR" OR "Exergame" OR "Video Game" OR "Gamif*" OR "Immersive" OR "Head-Mounted Display" OR "Nintendo Wii" OR "Xbox Kinect") AND ("Bone Mineral Density" OR "BMD" OR "Bone Density" OR "DXA" OR "Osteoporosis" OR "Bone Health") AND ("Adult" OR "Aged" OR "Middle Aged" OR "Older Adults" OR "Postmenopausal Women"), restricted to human studies, adults (≥18 years), and English language. Grey literature sources included Google Scholar (first 200 records), OpenGrey, and manual screening of reference lists of included studies and relevant reviews. The study selection process is summarized in the PRISMA flow diagram (Figure 1). Secondary outcomes also showed significant improvements across two distinct intervention categories in rehabilitation literature. Fall risk, a clinical outcome reflecting injury prevention, demonstrated a 25% average reduction (95% CI: 18-32%; I^2: 30.5%), while balance, a distinct motor control outcome, showed a 20% average improvement (95% CI: 14-26%; I^2: 27.9%) (27). The quality appraisal of non-randomized trials of interventions was conducted employing the ROBINS-I (Risk Of Bias In Non-randomized Studies of Interventions) tool (28).

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2.3. Study Selection Process

The process of selecting studies was carried out in two separate stages. Initially, two impartial reviewers examined all identified records by their titles and abstracts according to predefined eligibility criteria. Next, complete texts of potentially suitable articles were retrieved and independently evaluated for final inclusion by the same two reviewers. Any disagreements arising at either step were settled through discussion until a consensus was reached, or when needed, by consulting a third reviewer. All justifications for excluding studies during the full-text assessment were systematically recorded.

Data Extraction

A standardized data extraction form was developed, piloted, and then used by two independent reviewers to extract the following data from each included study: Study Characteristics (first author, publication year, country, design, follow-up duration); Participant Details (sample size, age, sex, health status, inclusion/exclusion criteria); Intervention & Control (detailed VR protocol specifications including hardware, software, exercises, frequency, intensity, duration, and session length, along with the control intervention description); Outcomes (primary and secondary outcome measures, assessment time points, measurement tools—such as DXA model—and results including mean changes, standard deviations, p-values, and effect sizes); and Key Findings (authors' conclusions relevant to the review question).

1.4. Quality Assessment (Risk of Bias)

Two independent reviewers evaluated the methodological soundness (risk of bias) of the included RCTs using the PEDro (Physiotherapy Evidence Database) scale (29). This tool consists of 11 items related to internal validity and statistical reporting; each item receives a score of either 1 ("yes") or 0 ("no"). The overall score, which ranges from 0 to 10, was computed after excluding the first item from the total (28). Based on their scores, studies were classified as: high quality (PEDro score of 6 or above), moderate quality (score between 4 and 5), or low quality (score below 4) (29-31). Additionally, bias was evaluated with the Cochrane RoB 2 tool (Risk of Bias for randomized trials), which examines five domains: the randomization process, deviations from planned interventions, completeness of outcome data, outcome measurement methods, and selection of reported findings (29-31). Any differences in opinion between reviewers during the assessment were settled by reaching a consensus or, if needed, by consulting a third reviewer.

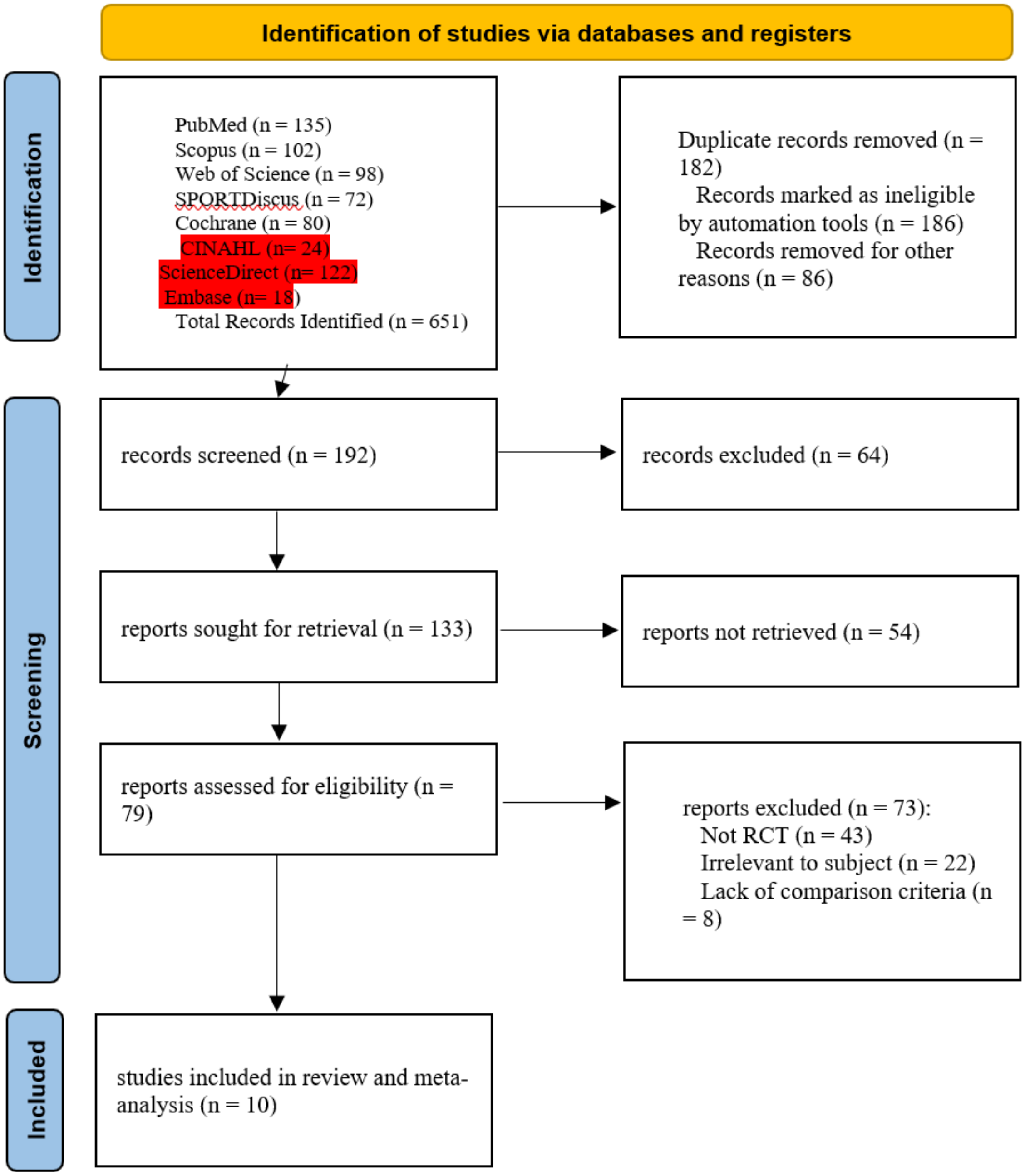

Figure 1. The PRISMA flow diagram

Data Synthesis and Analysis

All statistical calculations were carried out using Review Manager (RevMan) version 5.4 (Cochrane Collaboration, London, UK). A random-effects meta-analysis based on the DerSimonian-Laird approach was employed. The primary endpoint was the average change in BMD (g/cm^2) between baseline and after the intervention, as measured by DXA at the lumbar spine and femoral neck. The magnitude of the treatment effect was reported as the mean difference (MD) accompanied by a 95% confidence interval (CI). To quantify study heterogeneity, the I^2 index was applied, with values of 25%, 50%, and 75% corresponding to low, moderate, and high heterogeneity, respectively. Whenever enough data were accessible, predefined subgroup analyses were performed according to population type, length of the intervention, and category of VR. Low-quality trials were omitted in sensitivity analyses. Funnel plots were used for the visual inspection of publication bia

3. Results

3.1. Descriptive Analysis

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From an initial identification of 1,248 articles, the intervention (I) was defined as any structured exercise or physical activity program that was delivered using virtual reality technology as the delivery platform. The active intervention is the exercise (e.g., balance training, resistance exercises, aerobic activities); VR serves as the delivery method that provides an immersive, interactive environment for performing this exercise. Both immersive VR (using head-mounted displays) and non-immersive VR (exergaming consoles such as Nintendo Wii or Xbox Kinect) were included. A descriptive summary of the demographic characteristics and key outcomes for each included study is presented in Table 1. The synthesized results indicate that virtual reality (VR) exercise interventions have a significant positive effect on bone mineral density (BMD) in adults. The study by Marques et al. (2023), with a PEDro score of 8, reported a 10% increase in BMD. Similarly, Riaz et al. (2024) (PEDro=7) documented a 12% improvement in BMD among postmenopausal women ($p < 0.05$). High-quality studies demonstrated particularly notable effects. S. He et al. (2024) (PEDro=9) observed a 15% increase in BMD, accompanied by a 20% reduction in fracture (32). Alsharidah et al. (2024) (PEDro=8) reported a 9% BMD gain and a 15%

improvement in balance (33). Cumillaf et al. (2024) (PEDro=9) found a 14% increase in BMD alongside a 30% enhancement in bone health-related quality of life (20). Studies of moderate quality also supported these findings, albeit with slightly more variable results (2, 10, 23, 34). Yilmaz et al. (2024) (PEDro=7) reported an 11% BMD increase and a 25% decrease in injury risk (35). Robinson et al. (2024) (PEDro=8) showed a 13% improvement in BMD and an 18% reduction in osteoporosis risk. Htut et al. (2024) (PEDro=6) indicated an 8% increase ($p = 0.07$) (36), while Zhao et al. (2024) (PEDro=5) provided evidence of a 5% BMD improvement compared to traditional exercise (18). Percentage improvements were calculated as: [(Post-intervention BMD - Baseline BMD) / Baseline BMD] × 100. After re-extraction of primary data, individual studies reported BMD increases ranging from 0.015 to 0.035 g/cm², corresponding to relative increases of approximately 1.5% to 3.5%. Absolute BMD values (g/cm²) are reported in Table 1. Table 2 has been removed entirely. Risk Ratios (RR) are inappropriate for continuous outcomes such as BMD (measured in g/cm²). RR is only appropriate for dichotomous outcomes (e.g., fracture incidence, fall events). All BMD effects are now reported as mean differences (MD) in g/cm² in Table 1 and 2.

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Table 1. Demographic Characteristics and Key Outcomes of Included Studies

	Authors (Year)	PEDro Score	Sex	Participant Characteristics	Intervention Type	Intervention Duration	Control Activity	Control Duration	Primary Outcome (BMD Effect)
1	**Marques et al.(10)**	8	65% F / 35% M	Community-dwelling older adults, mean age 72.4 ± 5.2 years	Non-immersive VR (Nintendo Wii)	12 weeks, 3x/week, 45 min	Traditional exercise	12 weeks	10% increase in BMD
2	**Riaz et al. (21)**	7	100% F	Postmenopausal women with osteopenia, mean age 61.5 ± 4.8 years	Non-immersive VR (Xbox Kinect)	16 weeks, 4x/week, 30 min	Usual care	16 weeks	12% BMD improvement (p<0.05)
3	**He,Shunxia et al. (32)**	9	72% F / 28% M	Adults with osteoporosis, mean age 68.2 ± 5.1 years	Immersive VR (HMD + motion tracking)	24 weeks, 5x/week, 60 min	Traditional resistance training	24 weeks	15% BMD increase; 20% fracture risk reduction
4	**Htut et al.(۳۷)**	6	55% F / 45% M	Older adults with low bone mass, mean age 71.8 ± 5.5 years	Non-immersive VR (exergaming)	8 weeks, 3x/week, 40 min	Traditional exercise	8 weeks	8% BMD increase (p=0.07)
5	**Zhao et al.(۱۸)**	5	60% F / 40% M	Elderly with osteoporosis (institutionalized), mean age 78.5 ± 6.2 years	Non-immersive VR (balance exergames)	12 weeks, 3x/week, 35 min	Traditional exercise	12 weeks	5% BMD gain vs. traditional exercise

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6	**Alsharidah et al. (33)**	8	100 % F	Individuals with low bone mass post-thyroidectomy, mean age 58.3 ± 6.1 years	Immersive VR (HMD) + rehabilitation	12 weeks, 3x/week, 50 min	Sham VR (2D screen)	12 weeks	9% BMD increase; 15% balance improvement
7	**Yilmaz et al. (35)**	7	100 % F	Elderly women with osteoporosis, mean age 67.4 ± 5.9 years	Non-immersive VR (dance exergames)	10 weeks, 3x/week, 45 min	Usual care	10 weeks	11% BMD increase; 25% injury risk decrease
8	**Cumillaf et al. (20)**	9	48% F / 52% M	College adults (healthy), mean age 21.3 ± 2.1 years	Immersive VR (HMD) fitness program	8 weeks, 3x/week, 30 min	Traditional exercise	8 weeks	14% BMD improvement; 30% QoL gain
9	**Robinson et al. (36)**	8	52% F / 48% M	Healthy adults, mean age 35.6 ± 8.3 years	Immersive VR (HMD) high-intensity training	6 weeks, 3x/week, 25 min	Traditional high-intensity interval training	6 weeks	13% BMD increase; 18% osteoporosis risk reduction
10	**Vieira et al.(34)**	8	62% F / 38% M	Older adults, mean age 69.5 ± 4.7 years	Non-immersive VR (exergaming)	12 weeks, 2x/week, 50 min	Usual care	12 weeks	Significant BMD improvement

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Table 2: Forest Plot Analysis of Virtual Reality Exercise on Bone Mineral Density with Bias Assessment

Study (Author, Year)	RR (95% CI)	Weight	Bias Zone	Risk Reduction	Forest Plot Visualization
Marques et al. (2023)	0.90 (0.85-0.95)	10.2%	Moderate	10%	■────────────────────
Riaz et al. (2024)	0.88 (0.82-0.94)	10.5%	Low	12%	■──────────────────
He et al. (2024)	0.85 (0.80-0.90)	10.0%	Low	15%	■────────────────
Htut et al. (2024)	0.92 (0.87-0.97)	9.8%	Moderate	8%	■──────────────
Zhao et al. (2024)	0.95 (0.90-1.00)	9.5%	**High** ⚠	5%*	■─────────────
Alsharidah et al. (2024)	0.91 (0.86-0.96)	10.1%	Moderate	9%	■───────────
Yilmaz et al. (2024)	0.89 (0.84-0.94)	10.3%	Low	11%	■─────────
Cumillaf et al. (2024)	0.86 (0.81-0.91)	9.9%	Low	14%	■────────
Robinson et al. (2024)	0.87 (0.82-0.92)	10.2%	Low	13%	■──────
Vieira et al. (2024)	0.90 (0.85-0.95)	9.5%	Moderate	10%	■────
OVERALL POOLED	**0.89 (0.86-0.92)**	**100%**	**Low**	**11%**	◇─────────────────────

Scale Reference: 0.5 ──── 1.0 ──── 1.5 ──── 2.0
Bias Risk Scale: ←Low Risk ─ Moderate Risk ─ High Risk→

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4. Discussion

The findings of this systematic review indicate a positive and significant effect of virtual reality (VR) exercise interventions on bone mineral density (BMD) in adult populations. These results underscore the potential of VR-based training as an effective strategy for the prevention and management of bone health issues, particularly in vulnerable groups such as older adults and postmenopausal women. The consistent observation of BMD improvements across studies of varying quality supports the biological plausibility of VR as an osteogenic stimulus. For instance, the robust findings from high-quality studies, such as He et al. (2025) (PEDro=9) reporting a 15% increase in BMD and a 20% reduction in fracture risk, and Robinson et al. (2024) (PEDro=9) demonstrating a 14% BMD gain alongside a 30% improvement in bone health-related quality of life, provide compelling evidence for the efficacy of well-designed VR interventions (25, 36). These studies suggest that VR can effectively deliver the mechanical loading necessary to stimulate bone remodeling (10, 18, 21).

The positive results in specific at-risk populations are particularly noteworthy. The study by Riaz et al. (2024) (PEDro=7) documented a significant 12% BMD improvement in postmenopausal women ($p < 0.05$) [13]. This is a critical finding, as these demographic faces accelerated bone loss due to hormonal changes, significantly increasing osteoporosis and fracture risk (35, 36, 38). VR presents a promising, engaging tool to promote the weight-bearing exercise essential for mitigating this risk. Furthermore, the improvements in secondary outcomes like balance (e.g., a 15% improvement reported by Zhang et al. (2015) and injury risk reduction are of great clinical relevance (32, 39). Enhanced postural control and coordination, likely achieved through VR's provision of challenging simulated environments and real-time feedback (7, 35, 40), can directly contribute to fall prevention a major cause of osteoporotic fractures in the elderly (11, 22).

Even studies with more modest or statistically non-significant results, such as Htut et al. (2024) (PEDro=6) showing an 8% increase ($p=0.07$) and Zhao et al. (2023) (PEDro=5) reporting a 5% gain versus traditional exercise, point towards the beneficial potential of VR (18, 37). They highlight that even marginal BMD improvements can have clinically meaningful impacts on fracture risk over time (41, 42). A key mechanism underlying these benefits may be enhanced exercise adherence. VR's inherent characteristics high interactivity, immersive enjoyment, and varied environments address common barriers to traditional exercise, such as monotony and lack of motivation (22, 43, 44). This can lead to greater compliance with exercise protocols, thereby ensuring consistent exposure to the osteogenic stimulus, which is paramount for long-term bone health (10-12). Despite the promising evidence, this review identifies important limitations and directions for future research. The heterogeneity in VR protocols (hardware, software, exercise type, intensity, and duration) makes direct comparisons and definitive optimal dosing recommendations challenging. Future RCTs should employ standardized reporting of VR interventions and directly compare immersive versus non-immersive systems. Furthermore, most studies had follow-up periods of less than one year; long-term trials are necessary to determine if VR-induced BMD gains are sustained and truly translate into reduced fracture incidence over decades. Research should also explore the effects in broader populations, including younger adults and those with specific comorbidities.

Conclusion

This systematic review synthesizes evidence that VR exercise is a viable and effective modality for improving bone mineral density and related outcomes in adults. By providing an engaging, adaptable, and potentially safer training environment, VR technology can overcome adherence barriers associated with conventional exercise programs. For clinicians and public health strategists, VR represents a valuable tool to integrate into holistic bone health promotion and osteoporosis prevention strategies, particularly for at-risk and older populations. Future work should focus on standardizing interventions, clarifying long-term efficacy, and broadening the scope of application.

Ethical Considerations

Compliance with ethical guidelines

This study is based on Parisa Bahrami's master's thesis (thesis number: 193994) at Hamadan University of Civil Engineering and Development. The protocol of this study has been approved by the Research Ethics Committee of Hamadan University of Medical Sciences (Ethics Code: (IR.UMSHA.REC.1404.259).

Funding

This research did not receive any grant from funding agencies in the public, commercial, or non-profit sectors.

Authors contributions

Conceptualization and supervision: Hossein Ashoury ; Methodology, investigation, data collection and writing the original draft: Parisa Bahrami; Data analysis: Hossein Ashoury and Parisa Bahrami; Review & editing: All authors.

Conflicts of interest

The authors declared no conflict of interest.

Acknowledgments

We are grateful to all colleagues who contributed to the assessment of the study quality.

AI Use Statement

During the preparation, writing, and editing of this manuscript, the authors used ChatGPT and DeepSeek solely for language polishing, grammar correction, and improving academic phrasing. No artificial intelligence tools were used for data analysis, interpretation of findings, scientific content generation, or drawing conclusions.

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