Zhao *et al. Journal of Orthopaedic Surgery and Research* (2025) 20:523
https://doi.org/10.1186/s13018-025-05890-1

Journal of Orthopaedic Surgery and Research

SYSTEMATIC REVIEW 

# Optimal resistance training parameters for improving bone mineral density in postmenopausal women: a systematic review and meta-analysis

Fang Zhao[1,6†], Wenbo Su[1*†], Yaowei Sun[2], Jing Wang[3], Bin Lu[3,4] and Hezhang Yun[3,5*]


## Abstract

**Background** This meta-analysis aims to explore the effects of resistance training on bone mineral density (BMD) in postmenopausal women, specifically focusing on different training intensities, durations, frequencies, and periods, across various skeletal sites lumbar spine (LS), femoral neck (FN), total hip (TH), and trochanter (Troch).

**Methods** We systematically searched PubMed, Embase, Web of Science, and the Cochrane Library for studies evaluating the impact of resistance training programs on BMD in postmenopausal women, covering all records up to March 2025. Two reviewers independently screened the studies, extracted data, assessed the risk of bias using the Cochrane Handbook, and performed the meta-analysis using RevMan 5.4 and Stata 18 software.

**Results** 17 randomized controlled trials involving 690 subjects were included. The results indicate that resistance training significantly improves BMD at the LS (SMD = 0.88, 95% CI [0.21, 1.56], $P = 0.01$, $I^2 = 91\%$), FN (SMD = 0.89, 95% CI [0.40, 1.39], $P = 0.0004$, $I^2 = 87\%$) and TH (SMD = 0.30, 95% CI [0.10, 0.50], $P = 0.003$, $I^2 = 25\%$). However, no significant effect was observed on Troch bone density (SMD = 0.23, 95% CI [-0.01, 0.47], $P = 0.06$, $I^2 = 19\%$). Subgroup analysis further revealed that high-intensity training (≥ 70% 1RM) had a significant effect on the TH and FN ($P < 0.05$); training three times per week significantly improved bone mineral density at the LS, FN, TH, and Troch ($P < 0.05$); intervention durations of ≥ 48 weeks had a significant impact on FN and TH ($P < 0.05$); and sessions lasting 40 min had a significant effect on LS ($P < 0.05$).

**Conclusion** Resistance training can beneficially influence BMD in postmenopausal women, particularly at the LS, FN, and TH. A high-intensity training regimen (≥ 70% 1RM) performed three times per week with a longer training duration may be optimal. However, significant heterogeneity among the included studies for LS and FN bone density may affect the accuracy of the pooled results, thereby limiting the generalizability of these findings. More high-quality clinical trials are needed to confirm these findings.


†Fang Zhao and Wenbo Su contributed equally to this work.

*Correspondence:
Wenbo Su
suwb@lzu.edu.cn
Hezhang Yun
runhzdyx@bsu.edu.cn
Full list of author information is available at the end of the article

**Keywords** Resistance training, Postmenopausal, Women, Bone density, Meta-analysis

## Introduction

Osteoporosis in postmenopausal women is a global health issue that poses severe health risks and diminishes quality of life [1, 2]. As estrogen levels decline, postmenopausal women experience accelerated bone loss, leading to decreased bone density and mass, thereby increasing the brittleness of bones and the risk of fractures. This can result in pain, disability, and a loss of functional independence, severely affecting quality of life [2–5]. Furthermore, the deterioration of bone structure and the decrease in bone mass further increase the incidence of pathological osteoporotic fractures [6]. It is reported that approximately 40% of women over the age of 50 will suffer from osteoporotic fractures during their remaining lifetimes, with hip fractures particularly associated with high morbidity and mortality [7]. This worrying trend highlights the substantial negative impact of osteoporosis and fractures on patients' health and lives. Although several medications, including bisphosphonates, selective estrogen receptor modulators, and receptor activator of nuclear factor κB ligand inhibitors, have been approved for the treatment of postmenopausal osteoporosis, they have not been fully effective in reducing fracture incidence and may be associated with adverse effects and issues related to patient compliance [8–11].

Exercise training, especially resistance training, is recognized as a non-pharmacological intervention that can increase muscle strength and promote bone formation, effectively improving symptoms of osteoporosis and enhancing bone density [12–14]. Mechanistically, one pathway involves exercise-induced mechanical stimuli upregulating Wnt1 expression. Wnt1 binds to the LRP5/6 co-receptor, activating intracellular Dishevelled, which leads to release of free β-catenin and its translocation into the nucleus. Nuclear β-catenin associates with TCF/LEF transcription factors to induce and activate Runx2, Osterix, and Cyclin D1, thereby driving osteoblast differentiation and increasing bone mass. Concurrently, mechanical loading of osteocytes downregulates the expression and secretion of the Wnt antagonist sclerostin, which normally inhibits Wnt/β-catenin signaling by competitively binding to LRP5/6. In the absence of resistance-induced mechanical stimuli, Wnt1 levels decline and β-catenin undergoes ubiquitination and proteasomal degradation, resulting in downregulation of downstream osteogenic genes and subsequent bone loss [15–17]. On the other hand, resistance exercise elevates systemic growth factors such as insulin-like growth factor-1, which activates the PI3K–Akt–mTORC1 signaling pathway to stimulate muscle protein synthesis. The resulting increase in muscle mass and force production enhances mechanical loading on the skeleton, further contributing to improvements in bone strength [14]. Therefore, for postmenopausal women, resistance training serves as a crucial exercise modality. By contracting muscles against external resistance, it not only increases muscle strength but also promotes bone formation and reduces bone resorption, playing a vital role in the prevention and treatment of osteoporosis.

Despite extensive research exploring the effects of different resistance training modalities on bone density in postmenopausal women, there remains considerable debate over the most effective duration, intensity, and frequency of resistance training. Bae S et al. [18]. reported that resistance exercise at 50–85% 1RM, with 5–12 repetitions per set, performed 2–3 times weekly for 3–12 months, can improve bone mineral density in patients with osteoporosis. Oniszczuk, A et al. [17]. proposed that a training program using 75–85% 1RM- or alternatively light to moderate loads (30–70% 1RM)-with 8–12 repetitions per set, at least two sets per exercise, and 1–3 min of rest between sets, is beneficial for improving osteoporosis in older adults and preventing osteoporotic fractures. O'Bryan et al. [19]. recommended three weekly sessions at 75–80% 1RM, combined with weighted or impact-loading exercises (e.g., jumping or step training), performing 1–2 sets of each movement, to maximize concurrent gains in muscle strength and bone strength in older adults. Kistler-Fischbacher et al. [20]. demonstrated that an 8-month program of free-weight resistance exercises (deadlift, back squat, overhead press) at 80–85% 1RM-twice weekly, 5 sets of 5 repetitions per exercise per 40-minute session-together with one high-impact exercise (jump squat) and two balance exercises, effectively improved bone density in women with osteoporosis or low bone mass. Thus, this study aims to conduct a meta-analysis to systematically review and analyze existing research to explore the effects of various resistance training modalities on bone density in postmenopausal women. Comparing the impact of different durations, intensities, and frequencies of resistance training will provide scientific evidence for clinical practice, guiding the formulation of exercise intervention programs for postmenopausal women. This will aid in improving bone density, preventing osteoporosis, reducing the risk of fractures, and enhancing the quality of life and health status of postmenopausal women.

## Materials and methods

This study aims to investigate the effects of different resistance training modalities on bone mineral density in postmenopausal women through a systematic review and

**Table 1** Basic characteristics of included studies

| Study, Year | | Country | Sample size (IG/CG) | Age (IG/CG) | Intervention Method | Intervention Sets/reps | Inter-vention intensity | Frequency (times per week) | Duration | Duration per time (min) | Out-come |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bemben, 2000[a] [22] | USA | 10/8 | 50.5 ± 2.0/ 52.3 ± 1.4 | HI/CT | 3/8 | 80%1-RM | 3/w | 24 w | 45 min | LS/FN/TH/Troch | |
| Bemben, 2000[b] [22] | USA | 7/8 | 51.9 ± 2.3/ 52.3 ± 1.4 | LI/CT | 3/16 | 40%1-RM | 3/w | 24 w | 45 min | LS/FN/TH/Troch | |
| Bemben, 2010 [23] | USA | 22/12 | 64.0 ± 0.9/ 63.1 ± 11.4 | HI/CT | 3/10 | 80%1-RM | 3/w | 32 w | <60 min | LS/FN/TH/Troch | |
| Bocalini, 2009 [27] | Brazil | 15/10 | 69.0 ± 9.0/ 67.0 ± 8.0 | HI/CT | 3/10 | 85%1-RM | 3/w | 24 w | 50 min | LS/FN | |
| Bocalini, 2010 [28] | Brazil | 13/12 | 66.0 ± 9.0/ 64.0 ± 8.0 | MI/CT | 3/(10–12) | 60-70%1-RM | 3/w | 24 w | 60 min | LS/FN | |
| Chilibeck, 2002 [29] | Canada | 10/12 | 56.8 ± 2.0/ 58.8 ± 1.8 | HI/CT | 2/(8–10) | 70%1-RM | 3/w | 48 w | / | LS/FN/TH/Troch | |
| Chuin, 2009 [30] | Canada | 11/7 | 65.4 ± 3.5/ 67.4 ± 3.8 | HI/CT | 3/8 | 80%1-RM | 3/w | 24 w | 45 min | LS/FN | |
| Karinkanta, 2007 [32] | Finland | 37/37 | 72.7 ± 2.5/ 72.0 ± 2.1 | MI + HI/CT | First 6 weeks: 2/ (10–15) Other: 3/(8–10) | First 6 weeks:50–60%1-RM Other: 75–80%1-RM | 3/w | 48 w | 25–30 min | FN | |
| Maddalozzo, 2007 [24] | USA | 29/29 | 52.3 ± 3.3/ 52.5 ± 3.0 | MI/CT | 3/(8–12) | 60–75%1-RM | 2/w | 48 w | Ap-proximately 20–25 min | LS/FN/TH/Troch | |
| Marques, 2011 [33] | Portugal | 23/24 | 67.3 ± 5.2/ 67.9 ± 5.9 | MI + HI /CT | Initial Phase: 2/ (10–12) Later Phase: 2/ (6–8) | Initial Phase:60–70%1-RM Later Phase: 75–80%1-RM | 3/w | 32 w | 30–40 min | FN/TH/Troch | |
| Nelson, 1994 [25] | USA | 20/19 | 61.1 ± 3.7/ 57.3 ± 6.3 | HI/CT | 3/8 | 80%1-RM | 2/w | 52 w | Ap-proximately 35 min | LS/FN | |
| Pruitt, 1995[a] [26] | USA | 8/11 | 67.0 ± 0.5/ 69.6 ± 4.2 | HI/CT | 1/14 and 2/7 | 80%1-RM | 3/w | 48 w | 50–55 min | LS/FN/TH | |
| Pruitt, 1995[b] [26] | USA | 7/11 | 67.6 ± 1.4/ 69.6 ± 4.2 | LI/CT | 3/14 | 40%1-RM | 3/w | 48 w | 50–55 min | LS/FN/TH | |
| Rhodes, 2000 [31] | Canada | 20/18 | 68.8 ± 3.2/ 68.2 ± 3.5 | HI/CT | 3/8 | 75%1-RM | 3/w | 52 w | 40 min | LS/FN/Troch | |
| Verschueren, 2004 [34] | Belgium | 22/23 | 63.9 ± 3.8/ 64.2 ± 3.1 | MI/CT | For the first 14 weeks: 2/(8–20) For the following 10 weeks: 3/ (8–12) | For the first 14 weeks: 20-8RM (repetitions maximum) For the following 10 weeks: 12-8RM (repetitions maximum) | 3/w | 24w | Ap-proximately 40 min | LS/TH | |

**Table 1** (continued)

| Study, Year | | Country | Sample size (IG/CG) | Age (IG/CG) | Intervention Method | Intervention Sets/reps | Inter-vention intensity | Frequency (times per week) | Duration | Duration per time (min) | Out-come |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Holubiac, 2023 [35] | Romania | 20/19 | 56 ± 2.9/ 56.4 ± 2.1 | MI/CT | 2/12 | 6 sets at 70% 1RM + 6 sets at 50% 1RM | 2/w | 48 w | 50 min | FN/Troch | |
| Juesas, 2023a [36] | Spain | 35/12 | 69.17 ± 5.71/ 67.9 ± 8.60 | MI + HI/CT | First 8 weeks: 3 sets/ exercise, then increased to 4 sets/exercise after 24 weeks, 6–15 reps | 6 repetitions at 85% 1RM or 15 repetitions at 65–70% 1RM | 2/w | 32w | 55–60 min | LS/TH | |
| Juesas, 2023b [36] | Spain | 35/11 | 70.80 ± 5.86 72.00 ± 7.07 | MI + HI/CT | First 8 weeks: 3 sets/ exercise, then increased to 4 sets/exercise after 24 weeks, 6–15 reps | 6 repetitions at 85% 1RM or 15 repetitions at 65–70% 1RM | 2/w | 32w | 55–60 min | LS/TH | |
| Eslamipour, Fate-meh, 2023a [37] | Iran | 15/15 | 54.3 ± 3.5/ 53.1 ± 3.1 | HI/CT | 3/8 | 70–85% 1RM | 3/w | 24w | 20–60 min | LS/FN | |
| Eslamipour, Fate-meh, 2023b [37] | Iran | 15/15 | 53.2 ± 3.6/ 53.1 ± 3.1 | LI/CT | 3/16 | 40–60% 1RM | 3/w | 24 w | 20–60 min | LS/FN | |
| Abdul-Al, Obaida, 2024a [38] | Lebanon | 16/17 | 65.18 ± 3.52/ 65.47 ± 2.52 | MI + HI/CT | 3/10 | 5 repetitions at 85% 1RM + 5 repetitions at 65% 1RM | 2/w | 48w | 30–45 min | TH/FN | |
| Abdul-Al, Obaida, 2024b [38] | Lebanon | 16/17 | 65.41 ± 3.4/ 65.47 ± 2.52 | HI/CT | 3/10 | 75% 1RM | 2/w | 48w | 30–45 min | TH/FN | |

Note: CT = Control Group; IG = Intervention Group; LI = Low-Intensity Resistance Training; MI = Moderate-Intensity Resistance Training; HI = High-Intensity Resistance Training; LS = Lumbar Spine Bone Density; FN = Femoral Neck Bone Density; TH = Total Hip Bone Density; Troch = Greater Trochanter Bone Density; W = Weeks meta-analysis. The study adheres to the PRISMA 2020 guidelines for systematic reviews and employs the PICOS framework to formulate the research question and design. The PICOS framework includes Population (postmenopausal female subjects), Intervention (resistance training), Comparison (untrained healthy postmenopausal women), Outcomes (bone density at the LS, FN, TH and Troch), and Study Design (published randomized controlled trials). The research question addressed is, "What is the impact of different resistance training modalities on bone mineral density in postmenopausal women?"

#### Search strategy

To identify relevant studies, we employed a comprehensive literature search using the following keywords: "bone density," "density," "skeleton," "resistance training," "strength training," "weightlifting," "postmenopausal," and "exercise in the elderly," along with their synonyms, near-synonyms, and abbreviations. Our search strategy utilized a combination of MeSH terms and free-text terms across multiple databases, including PubMed, Embase, Web of Science, and the Cochrane Library. The search covered records from the inception of each database until March 2025, and involved tracking the references of relevant articles to ensure the inclusion of all studies meeting our criteria.

#### Inclusion and exclusion criteria

Inclusion Criteria: (1) Participants: Healthy postmenopausal women, aged 50 or above, without hypertension, diabetes, cardiovascular diseases, or related conditions, regardless of race and nationality; (2) Study Type: Published randomized controlled trials (RCTs); (3) Intervention Group: Resistance exercises of any intensity, form, and duration of ≥4 weeks; Control Group: No exercise intervention other than normal physical activity. (4) Outcome Measures: BMD of the LS, FN, TH and Troch, including at least one of the above indicators and one or more. (5) BMD measurement method used dual-energy X-ray absorptiometry (DXA).

Exclusion Criteria: (1) Adolescent literature, conference papers, and literature reviews; (2) Animal studies; (3) Studies where data were unavailable; (4) Inability to obtain the full text of the literature; (5) Non-English publications.

#### Study selection and data extraction

The search results were consolidated and imported into EndNote X9 software. Initially, duplicates were removed. Titles and abstracts were then screened according to the inclusion and exclusion criteria to discard non-qualifying studies. Full texts of potentially qualifying studies were reviewed for final inclusion. This process was independently conducted by two reviewers. In cases of uncertainty about inclusion or exclusion, the reviewers consulted each other to resolve the issue. If disagreements persisted, the article was reassessed, and a third researcher (H.Y.) adjudicated unresolved disputes. Full texts of all potentially eligible studies were obtained. Articles that did not meet the selection criteria were excluded. Any discrepancies were resolved in consultation with a third reviewer.

Data from the eligible studies were independently extracted by two reviewers using a pre-designed form. Extracted information included the first author, publication year, sample size, age, intervention modalities (intensity, duration, frequency etc.), and outcome measures. After completing the data extraction forms, reviewers cross-checked the data to ensure accuracy. All inconsistencies were resolved by a third reviewer (H.Y.). A detailed summary of the extracted data is presented in Table 1.

#### Assessment of methodological quality of included studies

The methodological quality of the included studies was assessed using the Cochrane Collaboration's risk of bias tool as outlined in the Cochrane Handbook for Systematic Reviews of Interventions, version 5.1.0 [21]. The assessment included seven domains: Random sequence generation; Allocation concealment; Blinding of participants and personnel; Blinding of outcome assessment; Incomplete outcome data; Selective reporting; Other bias. Studies were categorized as having low, high, or unclear risk of bias. The risk of bias assessment was independently conducted by two reviewers, with any disagreements resolved by a third reviewer (H.Y.).

#### Statistical analysis

Data were analyzed using RevMan 5.4 and Stata 18 software. The effect sizes were expressed as weighted mean differences (WMD) with 95% confidence intervals (CI). Heterogeneity was assessed using the $I^2$ statistic. If $I^2$ exceeded 50% and P was less than 0.10, indicating substantial heterogeneity, a random-effects model was employed; otherwise, a fixed-effect model was used. For outcomes with high $I^2$-indicating substantial variability-subgroup analyses and sensitivity analyses were performed. Subgroup analyses included factors such as Intervention Frequency, Intervention Intensity, Intervention Cycle, and Duration per time. Sensitivity analyses were conducted by excluding individual studies to assess each study's impact on the overall effect size, thereby verifying the stability of the meta-analytic results. When heterogeneity remained excessive and its origin could not be determined, descriptive analyses were employed.

## Results

### General results of the selected research literature

This study employed a rigorous and systematic search strategy to identify relevant papers from databases, retrieving a total of 4664 articles. EndNote software was used to remove 2554 duplicates, leaving 2110 articles for further screening. Subsequently, the titles and abstracts of the remaining articles were carefully evaluated based on predefined inclusion and exclusion criteria, resulting in the exclusion of 2022 articles. The remaining 88 articles underwent a comprehensive assessment, from which 17 RCTs were selected for inclusion in the meta-analysis. The specific screening process is illustrated in Fig. 1. This strict selection procedure ensured that only high-quality studies meeting the established criteria were included in the meta-analysis.

### Characteristics of included studies

All subjects included in the studies were healthy postmenopausal women, and the interventions were exclusively resistance training. A total of 690 participants were included in the analysis, with 375 assigned to the resistance training group and 315 to the control group. The geographical distribution of the 17 included studies spanned 11 countries: United States (5 studies) [22–26], Brazil (2 studies) [27, 28], Canada (3 studies) [29–31], with single studies conducted in Finland [32], Portugal [33], Belgium [34], Romania [35], Spain [36], Iran [37], and Lebanon [38]. The outcome measures included bone density at four sites: lumbar spine, femoral neck, total hip, and femoral trochanter. Regarding the intensity of resistance training (RT), according to the study by Borde et al. [39], intensities were categorized as follows: high intensity RT for 1RM ≥ 70%; moderate intensity RT for 51% ≤ 1RM ≤ 69%; and low intensity RT for 1RM ≤ 50%. For studies that did not match these load intensities, training was classified based on the number of repetitions per set: fewer than 6 repetitions were considered high intensity, 8–15 repetitions were considered moderate intensity, and more than 15 repetitions were considered low intensity.

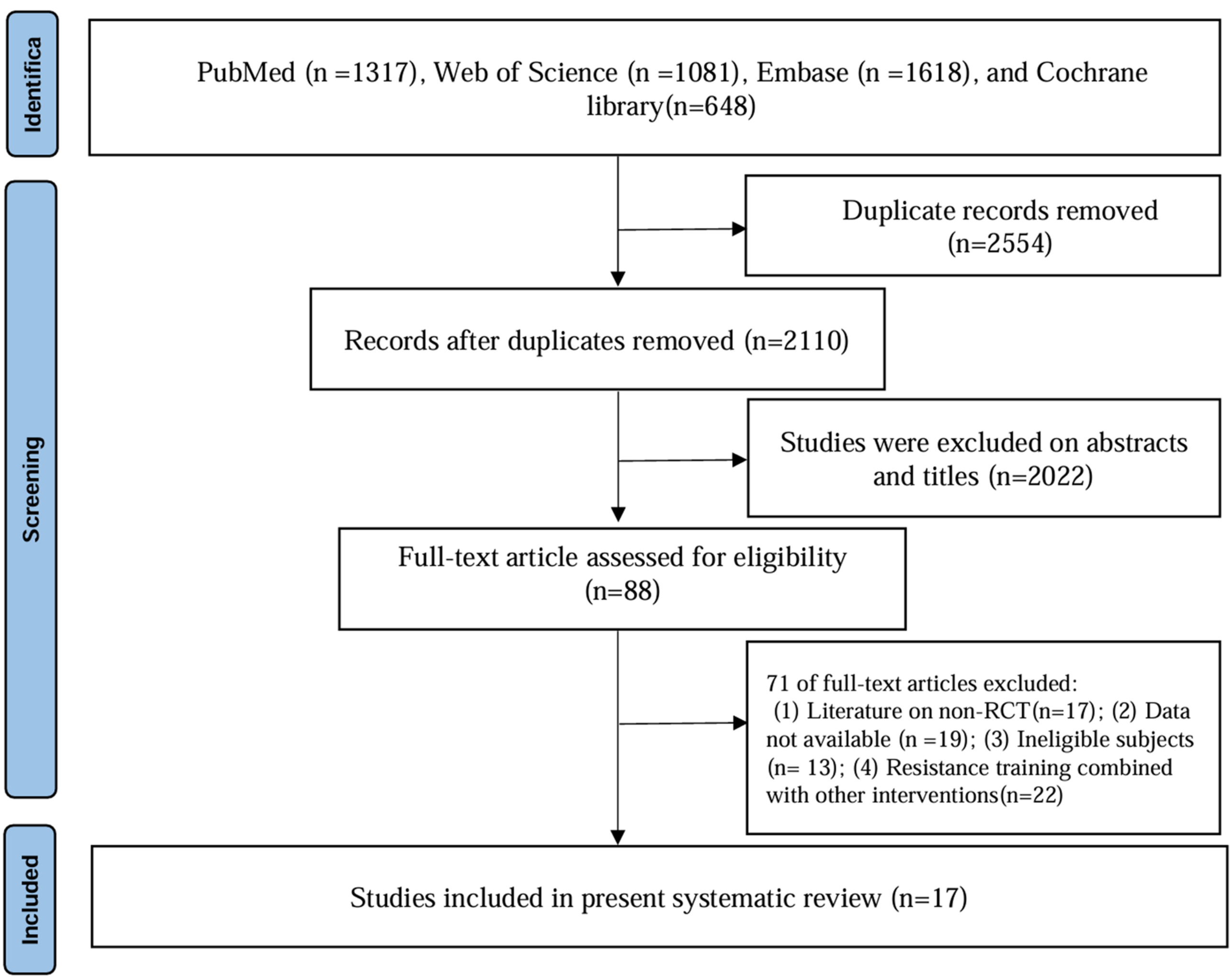


**Fig. 1** Flowchart of literature screening process

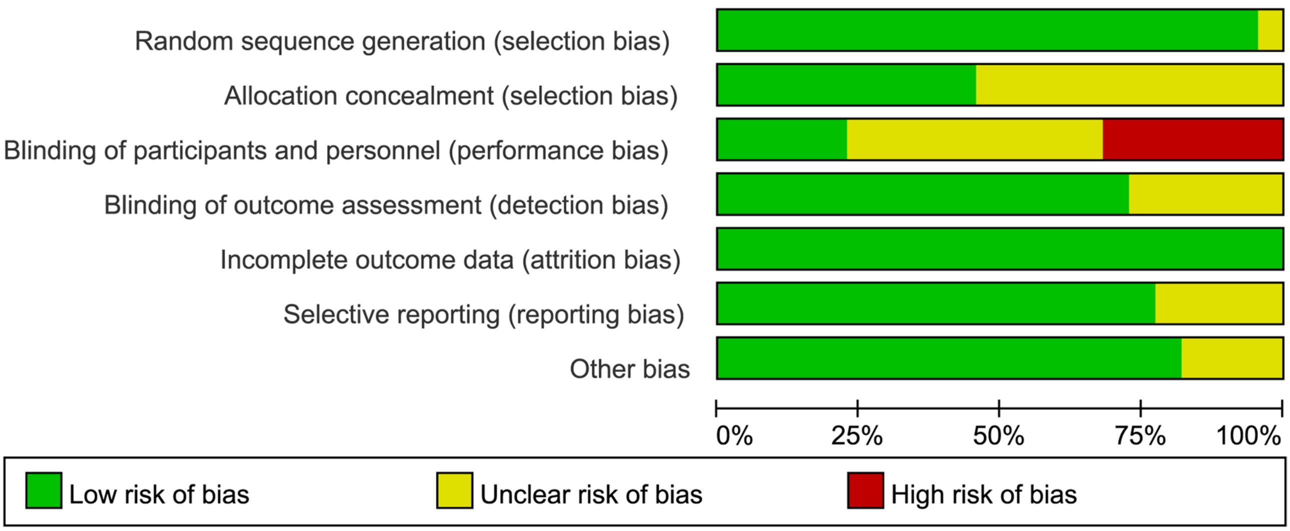


**Fig. 2** Risk of bias graph

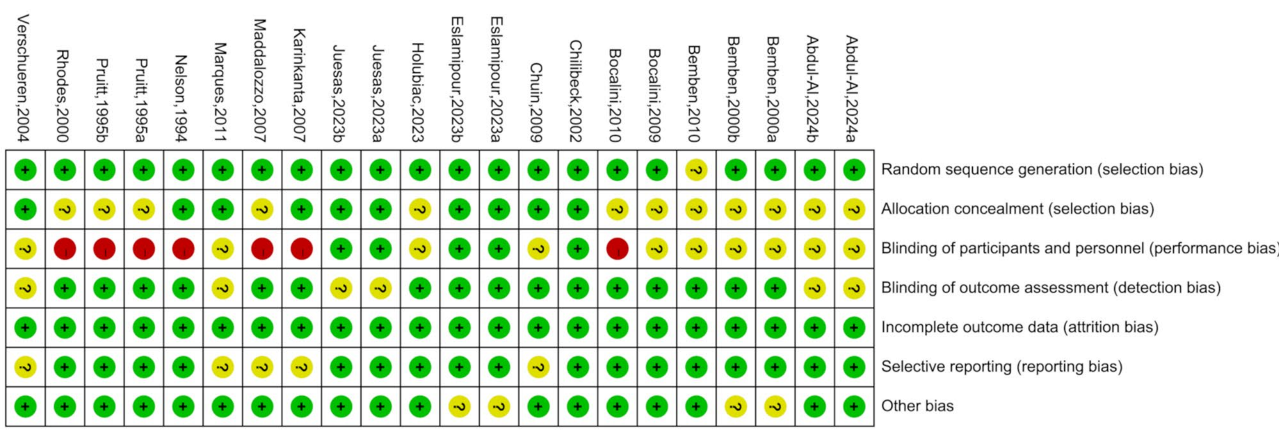


**Fig. 3** Risk of bias summary. "-" indicates high risk; "?" denotes some concerns; "+" signifies low risk

The specific characteristics of the included studies are presented in Table 1.

#### Quality assessment of selected articles

The results of the risk of bias assessment are presented in Figs. 2 and 3. Among the 17 studies included, green represents low risk, yellow denotes some concerns, and red represents high risk, providing a clear and visual description of each study's methodological quality. Overall, the methodological quality of the included studies is considered to be high.

#### The impact of resistance training on LS bone density

13 studies were included in the meta-analysis, comprising a total of 293 participants in the resistance training group and 233 participants in the control group. The analysis results are illustrated in Fig. 4. There was substantial heterogeneity among the 13 studies ($I^2 = 91\%$, $P < 0.00001$). Employing a random-effects model, the pooled effect size was SMD = 0.88, 95% CI [0.21, 1.56], Z = 2.58, $P = 0.01$, indicating significant differences ($P < 0.05$). This suggests that resistance training has statistically significant impact on LS bone density in postmenopausal women.

#### The impact of resistance training on FN bone density

15 studies were included in the meta-analysis, comprising a total of 314 participants in the resistance training group and 301 participants in the control group. The analysis results are illustrated in Fig. 5. There was substantial heterogeneity among the 15 studies ($I^2 = 87\%$, $P < 0.00001$). Employing a random-effects model, the pooled effect size was SMD = 0.89, 95% CI [0.40, 1.39], Z = 3.53, $P = 0.0004$, indicating significant differences ($P < 0.01$). This suggests that resistance training has a statistically significant impact on FN bone density in postmenopausal women.

| Study or Subgroup | Experimental Mean | Experimental SD | Experimental Total | Control Mean | Control SD | Control Total | Weight | Std. Mean Difference IV, Random, 95% CI |
|---|---|---|---|---|---|---|---|---|
| Bemben,2000a | 1.116 | 0.043 | 10 | 1.144 | 0.034 | 8 | 6.0% | -0.68 [-1.64, 0.28] |
| Bemben,2000b | 1.154 | 0.048 | 7 | 1.144 | 0.034 | 8 | 5.9% | 0.23 [-0.79, 1.25] |
| Bemben,2010 | 1.163 | 0.028 | 22 | 1.131 | 0.036 | 12 | 6.3% | 1.01 [0.26, 1.76] |
| Bocalini,2009 | 0.88 | 0.001 | 15 | 0.873 | 0.002 | 10 | 4.9% | 4.59 [2.99, 6.19] |
| Bocalini,2010 | 0.882 | 0.004 | 13 | 0.875 | 0.008 | 12 | 6.2% | 1.08 [0.23, 1.93] |
| Chilibeck,2002 | 0.885 | 0.037 | 10 | 0.937 | 0.031 | 12 | 6.0% | -1.48 [-2.45, -0.51] |
| Chuin,2009 | 1.06 | 0.16 | 11 | 1 | 0.16 | 7 | 6.0% | 0.36 [-0.60, 1.31] |
| Eslamipour,2023a | 1.06 | 0.03 | 15 | 0.78 | 0.03 | 15 | 3.4% | 9.08 [6.51, 11.65] |
| Eslamipour,2023b | 0.95 | 0.03 | 15 | 0.78 | 0.03 | 15 | 4.8% | 5.51 [3.85, 7.17] |
| Juesas,2023a | 0.84 | 0.13 | 35 | 0.81 | 0.08 | 12 | 6.4% | 0.25 [-0.41, 0.90] |
| Juesas,2023b | 0.88 | 0.13 | 35 | 0.88 | 0.15 | 11 | 6.4% | 0.00 [-0.68, 0.68] |
| Maddalozzo,2007 | 0.974 | 0.13 | 29 | 0.916 | 0.09 | 29 | 6.6% | 0.51 [-0.01, 1.04] |
| Nelson,1994 | 0.967 | 0.035 | 20 | 1.029 | 0.033 | 19 | 6.3% | -1.78 [-2.54, -1.03] |
| Pruitt,1995a | 0.947 | 0.159 | 7 | 0.901 | 0.158 | 11 | 6.0% | 0.28 [-0.68, 1.23] |
| Pruitt,1995b | 1.084 | 0.178 | 7 | 0.901 | 0.158 | 11 | 5.9% | 1.05 [0.03, 2.08] |
| Rhodes,2000 | 1.13 | 0.18 | 20 | 1.01 | 0.17 | 18 | 6.4% | 0.67 [0.01, 1.33] |
| Verschueren,2004 | 0.901 | 0.135 | 22 | 0.93 | 0.146 | 23 | 6.5% | -0.20 [-0.79, 0.38] |
| **Total (95% CI)** | | | **293** | | | **233** | **100.0%** | **0.88 [0.21, 1.56]** |

Heterogeneity: Tau² = 1.72; Chi² = 170.95, df = 16 (P < 0.00001); I² = 91%
Test for overall effect: Z = 2.58 (P = 0.010)

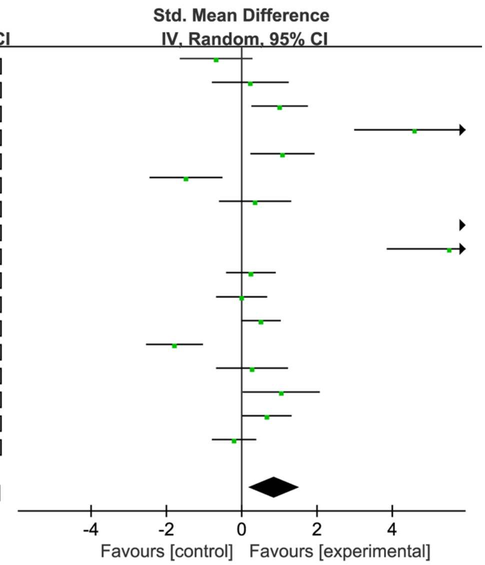


**Fig. 4** Forest plot of the effect of resistance training on LS bone density

| Study or Subgroup | Experimental Mean | Experimental SD | Experimental Total | Control Mean | Control SD | Control Total | Weight | Std. Mean Difference IV, Random, 95% CI |
|---|---|---|---|---|---|---|---|---|
| Abdul-Al,2024a | 0.832 | 0.091 | 16 | 0.751 | 0.07 | 17 | 5.7% | 0.98 [0.25, 1.70] |
| Abdul-Al,2024b | 0.83 | 0.117 | 16 | 0.751 | 0.07 | 17 | 5.7% | 0.81 [0.09, 1.52] |
| Bemben,2000a | 0.903 | 0.045 | 10 | 0.931 | 0.048 | 8 | 5.2% | -0.58 [-1.53, 0.38] |
| Bemben,2000b | 0.921 | 0.062 | 7 | 0.931 | 0.048 | 8 | 5.1% | -0.17 [-1.19, 0.85] |
| Bemben,2010 | 0.898 | 0.021 | 22 | 0.905 | 0.026 | 12 | 5.7% | -0.30 [-1.01, 0.41] |
| Bocalini,2009 | 0.704 | 0.001 | 15 | 0.695 | 0.001 | 10 | 2.2% | 8.70 [5.96, 11.45] |
| Bocalini,2010 | 0.701 | 0.004 | 13 | 0.693 | 0.005 | 12 | 5.3% | 1.72 [0.78, 2.66] |
| Chilibeck,2002 | 0.743 | 0.027 | 10 | 0.718 | 0.026 | 12 | 5.4% | 0.91 [0.02, 1.80] |
| Chuin,2009 | 0.91 | 0.08 | 11 | 0.9 | 0.07 | 7 | 5.2% | 0.12 [-0.82, 1.07] |
| Eslamipour,2023a | 0.82 | 0.02 | 15 | 0.69 | 0.02 | 15 | 3.4% | 6.32 [4.46, 8.18] |
| Eslamipour,2023b | 0.75 | 0.02 | 15 | 0.69 | 0.02 | 15 | 5.0% | 2.92 [1.85, 3.99] |
| Holubiac,2023 | 0.697 | 0.069 | 20 | 0.704 | 0.077 | 19 | 5.9% | -0.09 [-0.72, 0.53] |
| Karinkanta,2007 | 2.71 | 0.33 | 37 | 2.67 | 0.44 | 37 | 6.2% | 0.10 [-0.35, 0.56] |
| Maddalozzo,2007 | 0.745 | 0.09 | 29 | 0.728 | 0.08 | 29 | 6.1% | 0.20 [-0.32, 0.71] |
| Marques,2011 | 0.676 | 0.09 | 23 | 0.676 | 0.065 | 24 | 6.0% | 0.00 [-0.57, 0.57] |
| Nelson,1994 | 0.858 | 0.039 | 20 | 0.806 | 0.035 | 19 | 5.7% | 1.37 [0.67, 2.08] |
| Pruitt,1995a | 0.61 | 0.093 | 8 | 0.641 | 0.07 | 11 | 5.3% | -0.37 [-1.29, 0.55] |
| Pruitt,1995b | 0.7 | 0.142 | 7 | 0.641 | 0.07 | 11 | 5.2% | 0.55 [-0.42, 1.51] |
| Rhodes,2000 | 0.83 | 0.12 | 20 | 0.73 | 0.1 | 18 | 5.8% | 0.88 [0.21, 1.55] |
| **Total (95% CI)** | | | **314** | | | **301** | **100.0%** | **0.89 [0.40, 1.39]** |

Heterogeneity: Tau² = 0.98; Chi² = 134.47, df = 18 (P < 0.00001); I² = 87%
Test for overall effect: Z = 3.53 (P = 0.0004)

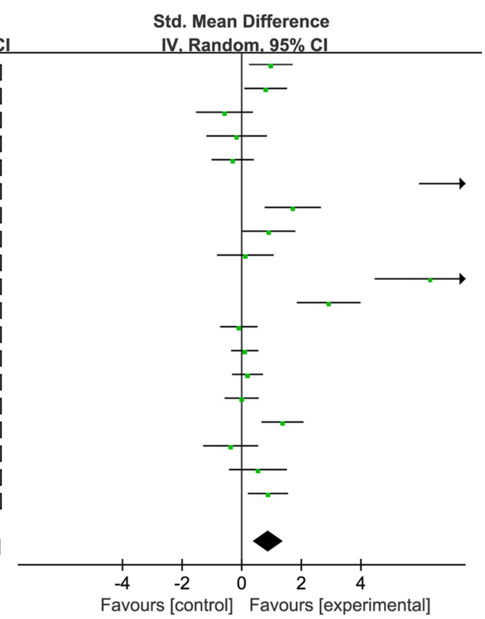


**Fig. 5** Forest plot of the effect of resistance training on FN bone density

### The impact of resistance training on TH bone density

9 studies were included in the meta-analysis, comprising a total of 240 participants in the resistance training group and 195 participants in the control group. The meta-analysis results are presented in Fig. 6. There was relatively low heterogeneity among the seven studies ($I^2 = 25\%$, $P = 0.20$). Employing a fixed-effects model, the pooled effect size was SMD = 0.30, 95% CI [0.10, 0.50], Z = 2.94, $P = 0.003$, indicating significant differences ($P < 0.01$). This suggests that resistance training has a statistically significant impact on TH bone density in postmenopausal women.

### The impact of resistance training on Troch bone density

7 studies were included in the meta-analysis, comprising a total of 141 participants in the resistance training group and 130 participants in the control group. The meta-analysis results are presented in Fig. 7. There was relatively low heterogeneity among the six studies ($I^2 = 19\%$, $P = 0.28$). Employing a fixed-effects model, the pooled effect size was SMD = 0.23, 95% CI [-0.01, 0.47], Z = 1.86, $P = 0.06$, indicating nonsignificant differences ($P > 0.05$).

### Results of subgroup analysis

We conducted subgroup analyses on LS, FN, TH, and Troch bone density in postmenopausal women. The

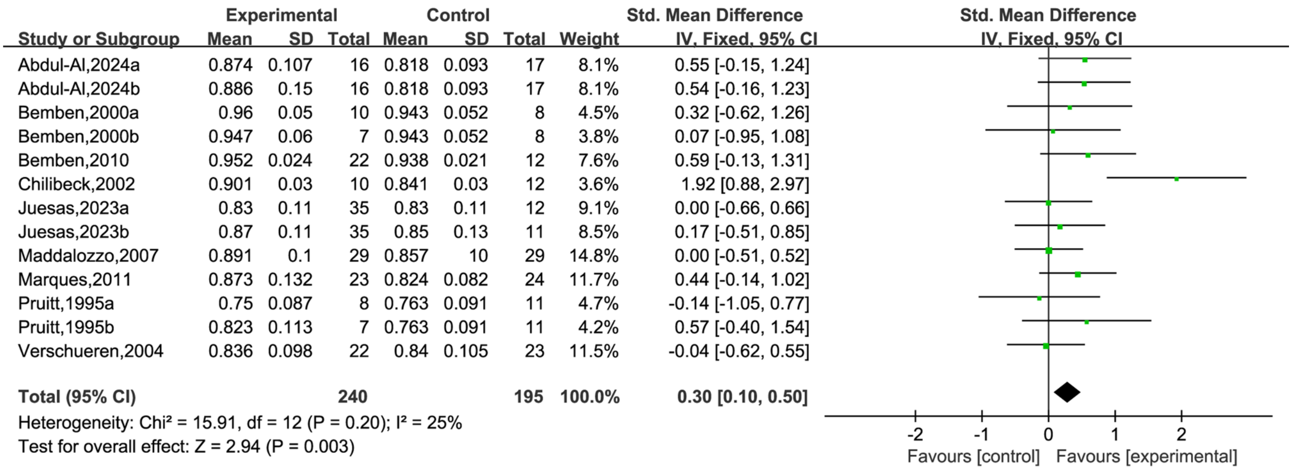


**Fig. 6** Forest plot of the effect of resistance training on TH bone density

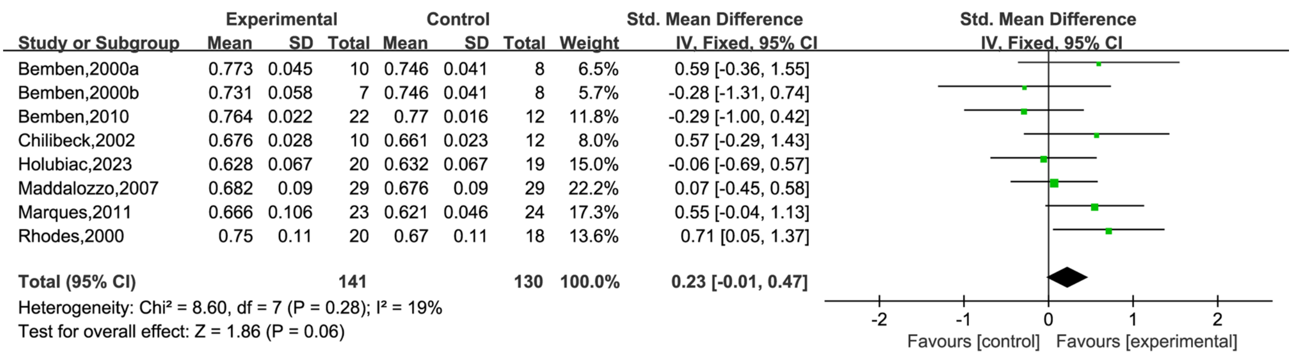


**Fig. 7** Forest plot of the effect of resistance training on troch bone density

subgroups included Intervention frequency, Intervention intensity, Intervention cycle, and Duration per time. The specific results are shown in Table 2.

#### *Intervention frequency*

In the comparison of intervention frequencies, we found significant differences ($P < 0.05$) in LS, FN, and TH indicators among different intervention frequencies. Interventions with a frequency of ≥ 3 times per week showed overall better effects on bone density in postmenopausal women, with statistically significant differences observed in LS, FN, TH, and Troch indicators ($P < 0.05$).

#### *Intervention intensity*

In the comparison of intervention intensities, we found significant differences ($P < 0.05$) in LS, FN, and TH indicators among different intervention intensities. High-intensity (HI) interventions showed overall better effects on bone density in postmenopausal women, especially with statistically significant differences in TH and FN indicators ($P < 0.05$).

#### *Intervention cycle*

In the comparison of intervention cycles, we found significant differences ($P < 0.05$) in LS, FN, and TH indicators among different intervention cycles. Interventions with a duration of 48 weeks or more showed statistically significant differences in FN and TH indicators ($P < 0.05$). Interventions with a duration of less than 48 weeks also showed statistically significant differences in lumbar LS and FN indicators ($P < 0.05$).

#### *Duration per time*

In the comparison of the duration per intervention, we found significant differences in FN and Troch indicators ($P < 0.05$). Interventions with a duration of ≥ 40 min per session showed overall better effects on bone density in postmenopausal women, with statistically significant differences particularly observed in the LS indicator ($P < 0.05$).

### Sensitivity analysis

The sensitivity analysis results are shown in Fig. 8. For FN and TH, excluding any single study had little impact on the pooled effect size and did not materially change its direction, indicating that the meta-analytic findings are

**Table 2** Subgroup analysis of the effects of different resistance exercise parameters on bone mineral density in postmenopausal women

| | LS | | | | | FN | | | | | TH | | | | | Troch | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | N | SMD | 95%CI | I²% | S | N | SMD | 95%CI | I²% | S | N | SMD | 95%CI | I²% | S | N | SMD | 95%CI | I²% |
| Intervention frequency | | | | | | | | | | | | | | | | | | | | |
| ≥3 times/week | 10 | 336 | 1.34 | 0.45 to 2.23 | 91 | 11 | 413 | 1.08 | 0.38 to 1.79 | 89 | 6 | 218 | 0.38 | 0.10 to 0.65 | 44 | 5 | 174 | 0.36 | 0.05 to 0.66 | 26 |
| <3 times/week | 2 | 190 | -0.23 | -1.18 to 0.71 | 88 | 4 | 202 | 0.62 | 0.10 to 1.14 | 69 | 3 | 217 | 0.30 | -0.07 to 0.50 | 0 | 2 | 97 | 0.02 | -0.38 to 0.41 | 0 |
| Intervention intensity | | | | | | | | | | | | | | | | | | | | |
| HI | 9 | 242 | 1.02 | -0.22 to 2.26 | 93 | 11 | 315 | 1.14 | 0.32 to 1.96 | 90 | 5 | 126 | 0.58 | 0.21 to 0.95 | 56 | 5 | 132 | 0.32 | -0.06 to 0.71 | 16 |
| MI | 3 | 128 | 0.42 | -0.26 to 1.09 | 70 | 2 | 83 | 0.90 | -0.58 to 2.39 | 87 | 2 | 103 | -0.01 | -0.40 to 0.37 | 0 | 1 | 58 | 0.07 | -0.45 to 0.58 | / |
| LI | 3 | 63 | 2.18 | -0.45 to 4.81 | 93 | 3 | 63 | 1.09 | -0.69 to 2.87 | 89 | 2 | 33 | 0.33 | -0.37 to 1.03 | 0 | 1 | 15 | -0.28 | -1.31 to 0.74 | / |
| MI + HI | / | / | / | / | | 3 | 154 | 0.30 | -0.22 to 0.83 | 60 | 4 | 173 | 0.29 | -0.03 to 0.62 | 0 | 1 | 47 | 0.55 | -0.04 to 1.13 | / |
| Intervention cycle | | | | | | | | | | | | | | | | | | | | |
| <48 W | 8 | 333 | 1.55 | 0.60 to 2.51 | 92 | 7 | 242 | 1.71 | 0.49 to 2.93 | 93 | 5 | 252 | 0.22 | -0.05 to 0.48 | 0 | 3 | 114 | 0.20 | -0.18 to 0.58 | 36 |
| ≥48 W | 5 | 193 | -0.12 | -1.04 to 0.80 | 88 | 8 | 268 | 0.52 | 0.18 to 0.85 | 58 | 4 | 183 | 0.40 | 0.10 to 0.70 | 59 | 4 | 157 | 0.25 | -0.06 to 0.57 | 22 |
| Duration per time | | | | | | | | | | | | | | | | | | | | |
| <40 min | 2 | 97 | -0.62 | -2.87to 1.63 | 96 | 4 | 218 | 0.37 | -0.15 to 0.90 | 72 | 2 | 105 | 0.20 | -0.19 to 0.58 | 18 | 2 | 105 | 0.28 | -0.11 to 0.66 | 32 |
| ≥40 min | 8 | 313 | 0.54 | 0.02 to 1.06 | 76 | 6 | 176 | 0.88 | -0.08 to 1.84 | 87 | 4 | 208 | 0.10 | -0.20 to 0.39 | 0 | 2 | 71 | 0.46 | -0.02 to 0.94 | 25 |

Note: LS = Lumbar Spine Bone Density; FN = Femoral Neck Bone Density; TH = Total Hip Bone Density; Troch = Greater Trochanter Bone Density;

robust. However, for LS, omission of one study [37] produced a significant shift in the overall pooled estimate; and for Troch, exclusion of two studies [22, 23] likewise led to a significant change in the pooled effect. It should be noted that, compared with the other outcomes, the LS and Troch results are less stable.

## Discussion

Women experience a loss of bone mineral content, disruption of trabecular bone structure, and a decline in bone load-bearing capacity as a result of reduced hormone secretion during menopause, increasing the risk of fractures [2, 40, 41]. Dual-energy X-ray absorptiometry is the primary tool used to assess BMD in several clinical practice guidelines [42, 43]. Current research confirms that resistance training plays a positive role in increasing or maintaining bone density [44, 45]. However, further research is needed to determine the optimal duration, intensity, frequency, and cycle of resistance exercises that can best improve or delay the loss of bone mineral content in postmenopausal women. It has been noted [46] that different exercise intensities (high, medium, low) have varied effects on the bone density of postmenopausal women. High-intensity exercise has been shown to be more effective in stimulating lumbar spine bone density than low and moderate intensities, but it does not affect femoral neck bone density. Moreover, the impact of different types of resistance exercises on the bone density of postmenopausal women also varies, with non-weight-bearing high-intensity exercise possibly being the most effective intervention for femoral neck BMD [47]. Therefore, in this study, our goal is to examine the effects of scientifically selected resistance training parameters—such as duration, intensity, cycle, and frequency—on the bone density (lumbar spine, femoral neck, total hip, femoral trochanter) of postmenopausal women.

In this study, resistance training effectively improved the bone density at the FN, TH, and LS in postmenopausal women, with significant differences observed ($P < 0.05$), aligning with results from previous studies [48–50]. However, the improvement in Troch bone density was not significant. Bone requires high-magnitude, dynamic weight-bearing loads to stimulate osteogenesis, and conventional resistance-training protocols may not generate sufficient strain at the lateral proximal femur, resulting in inadequate stimulation of the trochanteric region. This insufficiency is further exacerbated by the postmenopausal hormonal environment-low estrogen levels shift remodeling toward resorption and suppress osteoblast activity-so that even applied mechanical signals elicit a weaker anabolic response. Moreover, the inherently slow pace of bone remodeling means that resistance training may be insufficient to produce a measurable increase in bone mineral density at this site

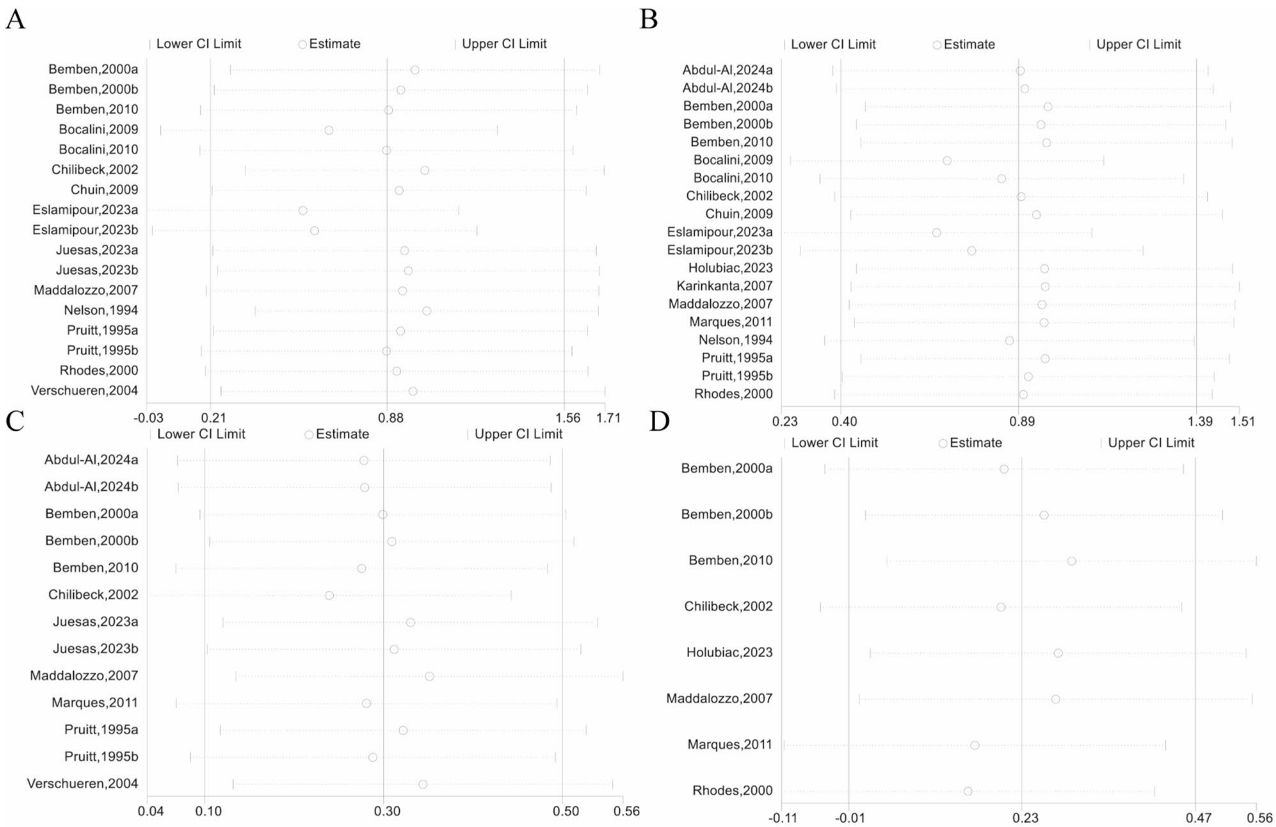


**Fig. 8** Sensitivity analysis of the effects of resistance training on LS (**A**), FN (**B**), TH (**C**), Troch (**D**) in postmenopausal women. LS = Lumbar Spine Bone Density; FN = Femoral Neck Bone Density; TH = Total Hip Bone Density; Troch = Greater Trochanter Bone Density

[50, 51]. In subgroup analyses, significant differences in intervention intensities were noted for FN, LS and TH indices ($P < 0.05$). High intensity (HI) interventions generally showed better outcomes for bone density in postmenopausal women, particularly for TH and FN indices, with statistically significant differences ($P < 0.05$), similar to findings by Vainionpää et al. [52]. Regarding different intervention frequencies, significant differences were observed across FN, TH, and LS indices ($P < 0.05$). Studies like O'Bryan et al. have also indicated that the frequency of exercise significantly impacts bone formation [19]. An intervention frequency of ≥3 times per week generally showed better effects on bone density in postmenopausal women, echoing findings by Borba-Pinheiro et al. [53], especially significant for LS, FN, and Troch indices ($P < 0.05$). Different intervention cycle also showed significant differences in FN, TH, and LS indicators ($P < 0.05$). Subgroup analysis indicated that interventions lasting ≥ 48 weeks demonstrated statistically significant effects on FN and TH indicators ($P < 0.05$), while interventions lasting < 48 weeks showed significant differences in LS and FN indicators ($P < 0.05$). In addition, interventions with a duration of ≥40 min per session generally had better effects on improving bone density, especially with statistically significant improvements in the LS indicator ($P < 0.05$).

Wang et al.'s study [50] suggests that, compared to high intensity, moderate intensity is superior in increasing BMD in postmenopausal women. Their findings contradict the results of this study, primarily due to different definitions of intensity. Wang et al. defined training intensity ≥ 80% 1RM as high intensity, 65 – 80% 1RM as moderate intensity, and ≤ 65% 1RM as low intensity. However, in this study, high intensity was defined as 1RM ≥ 70%, moderate intensity as 51% ≤1RM ≤ 69%, and low intensity as 1RM ≤ 50%. Different classifications of intensity may lead to inconsistent research results. However, lower intensity training did not show significant differences in BMD in postmenopausal women, possibly because lower loads often fail to reach the stress threshold required to stimulate bone tissue [34, 50, 54]. Furthermore, intervention duration also significantly influences BMD in postmenopausal women. Research suggests that bone remodeling cycles typically take three to four months, and achieving a new stable level of bone mass change usually requires 7–9 months [55]. This study further corroborates these findings, as the minimum intervention duration among the 17 included studies was 24 weeks. Consequently, subgroup analyses revealed statistically significant improvements in BMD for both intervention durations (≥48 weeks and <48 weeks, $P<0.05$). Fuchs et al.'s [55] also emphasized that that the length of intervention affects changes in bone density because bones require sufficient mechanical stimulation over time to adapt and remodel. Moreover, this stimulus must be sustained long enough to trigger an adaptive skeletal response. It is noteworthy that, due to the limited number of studies available for some subgroups, certain analyses included only a few eligible studies. Therefore, further studies with larger sample sizes and higher quality are needed to validate these conclusions.

The results of this study indicate that resistance exercise leads to beneficial improvements in BMD at the LS, FN, and TH in postmenopausal women. However, significant heterogeneity was observed in the BMD outcomes for the LS and FN, prompting the use of subgroup analyses and sensitivity analyses to address this issue. Subgroup analyses considered factors such as intervention frequency, intervention intensity, intervention duration, and intervention cycle. Unfortunately, despite these subgroup analyses, substantial heterogeneity persisted within the LS and FN outcomes. It is important to note that all included participants were postmenopausal women, with a mean age ranging from 50 to 72 years, and BMD was consistently measured using dual-energy X-ray absorptiometry. Sensitivity analyses were conducted by sequentially excluding individual studies to evaluate the robustness of the findings. We performed sensitivity analyses not only on LS and FN, where heterogeneity was higher, but also on TH and Troch, where heterogeneity was relatively lower, to ensure the reliability and stability of the pooled estimates. Notably, the exclusion of the study by Eslamipour et al. [37]. had a significant impact on the overall pooled effect size for LS, indicating that the results for this site may be less robust. Given these limitations, the findings of this meta-analysis should be interpreted as preliminary and should be validated by future high-quality clinical trials. Accordingly, caution is advised when recommending these results.

## Conclusions

Resistance training can beneficially influence BMD in postmenopausal women, particularly at the LS, FN, and TH. A high-intensity training regimen (≥70% 1RM) performed three times per week with a longer training duration may be optimal. However, significant heterogeneity among the included studies for LS and FN bone density may affect the accuracy of the pooled results, thereby limiting the generalizability of these findings. More high-quality clinical trials are needed to confirm these findings.

## Limitations and directions for future research

This study employed meta-analytic methods to evaluate the effects of varying resistance-training parameters on bone mineral density in postmenopausal women. However, several limitations should be acknowledged. The number of included studies was small, and some subgroup analyses were based on only a few eligible trials, precluding reliable conclusions. Although subgroup analyses were conducted to identify potential sources of heterogeneity, significant variability persisted across subgroups, which may compromise the accuracy of the pooled effect estimates and limit their generalizability. Notably, the literature search and selection process were restricted to English-language publications, potentially omitting important findings published in other languages and introducing language bias. Furthermore, published studies may be subject to publication bias, as trials with significant results are more likely to be published, whereas those with null or negative findings may remain unpublished. Future research should aim to minimize these biases by broadening language inclusion criteria and enhancing reporting transparency. Given these limitations, the results of this meta-analysis should be considered preliminary and warrant confirmation through additional high-quality clinical trials.

Future research could explore combined intervention models that integrate resistance training with other modalities-such as nutritional supplementation, aerobic exercise, or vibration therapy-to elicit synergistic effects and further enhance bone mineral density. Additionally, as most existing studies have focused on short-to mid-term outcomes, longer-term follow-up trials are needed to assess the sustained impact of resistance training on BMD and its role in fracture prevention. Research should also investigate personalized resistance-training protocols tailored to individual characteristics (e.g., baseline BMD, health status, training history) to improve intervention precision and efficacy. Finally, further studies are warranted to elucidate the cellular and molecular mechanisms underlying resistance-training-induced bone adaptation, thereby providing a scientific foundation for optimizing training regimens.

**Acknowledgements**
We sincerely appreciate the corresponding author, Dr. Hezhang Yun, for his meticulous revisions, valuable feedback, and careful review of the manuscript. We also extend our gratitude to our families, friends, and colleagues. Furthermore, we are grateful for the valuable contributions of each author.

**Author contributions**
Conceptualization, W.S., F.Z., and H.Y.; methodology, Y.S., and J.W.; software, B.L., J.W. and F.Z.; validation, H.Y. and W.S.; formal analysis, F.Z.; data curation, F.Z., and Y.S.; writing—original draft preparation, F.Z., and W.S.; writing—review and editing, W.S., and H.Y.; supervision, H.Y.; All authors have read and agreed to the published version of the manuscript.All authors reviewed the manuscript.

**Funding**
This research received no external funding.

**Data availability**
No datasets were generated or analysed during the current study.

## Declarations

**Institutional review board statement**
Not applicable, As this study does not involve any experiments related to animals or human subjects.

**Informed Consent**
Since this study does not involve humans, the Informed Consent Statement is not applicable..

**Competing interests**
The authors declare no competing interests.

**Author details**
[1]Department of Sports Teaching and Research, Lanzhou University, Lanzhou 73000, China
[2]School of Sport Science, Beijing Sport University, Beijing 100084, China
[3]School of Physical Education, Zhejiang Guangsha Vocational and Technical University of Construction, Dongyang 322100, China
[4]School of Education, Philippine Women's University, Manila 1004, Philippines
[5]Faculty of Health Sciences and Sports, Macao Polytechnic University, Macao 999078, China
[6]China Basketball College, Beijing Sport University, Beijing 100084, China

Received: 16 March 2025 / Accepted: 5 May 2025
Published online: 27 May 2025

**References**

1. Migliorini F, Maffulli N, Spiezia F, Peretti GM, Tingart M, Giorgino R. Potential of biomarkers during Pharmacological therapy setting for postmenopausal osteoporosis: a systematic review. J Orthop Surg Res. 2021;16(1):351.
2. Conti V, Russomanno G, Corbi G, Toro G, Simeon V, Filippelli W, Ferrara N, Grimaldi M, D'Argenio V, Maffulli N, Filippelli A. A polymorphism at the translation start site of the vitamin D receptor gene is associated with the response to anti-osteoporotic therapy in postmenopausal women from Southern Italy. Int J Mol Sci. 2015;16(3):5452–66.
3. Migliorini F, Giorgino R, Hildebrand F, Spiezia F, Peretti GM, Alessandri-Bonetti M, Eschweiler J, Maffulli N. Fragility Fractures: Risk Factors and Management in the Elderly. Medicina (Kaunas, Lithuania) 2021;57:(10).
4. Bao X, Liu C, Liu H, Wang Y, Xue P, Li Y. Association between polymorphisms of glucagon-like peptide-1 receptor gene and susceptibility to osteoporosis in Chinese postmenopausal women. J Orthop Surg Res. 2024;19(1):869.
5. Daly RM, Dalla Via J, Duckham RL, Fraser SF, Helge EW. Exercise for the prevention of osteoporosis in postmenopausal women: an evidence-based guide to the optimal prescription. Braz J Phys Ther. 2019;23(2):170–80.
6. Migliorini F, Colarossi G, Eschweiler J, Oliva F, Driessen A, Maffulli N. Antiresorptive treatments for corticosteroid-induced osteoporosis: a bayesian network meta-analysis. Br Med Bull. 2022;143(1):46–56.
7. Cheng C, Wentworth K, Shoback DM. New frontiers in osteoporosis therapy. Annu Rev Med. 2020;71:277–88.
8. Li SS, He SH, Xie PY, Li W, Zhang XX, Li TF, Li DF. Recent progresses in the treatment of osteoporosis. Front Pharmacol. 2021;12:717065.
9. Migliorini F, Maffulli N, Colarossi G, Eschweiler J, Tingart M, Betsch M. Effect of drugs on bone mineral density in postmenopausal osteoporosis: a bayesian network meta-analysis. J Orthop Surg Res. 2021;16(1):533.
10. Migliorini F, Maffulli N, Spiezia F, Tingart M, Maria PG, Riccardo G. Biomarkers as therapy monitoring for postmenopausal osteoporosis: a systematic review. J Orthop Surg Res. 2021;16(1):318.
11. Migliorini F, Colarossi G, Baroncini A, Eschweiler J, Tingart M, Maffulli N. Pharmacological management of postmenopausal osteoporosis: a level I evidence Based - Expert opinion. Expert Rev Clin Pharmacol. 2021;14(1):105–19.
12. Atlihan R, Kirk B, Duque G. Non-Pharmacological interventions in osteosarcopenia: A systematic review. J Nutr Health Aging. 2021;25(1):25–32.
13. Fares A. Pharmacological and Non-pharmacological means for prevention of fractures among elderly. Int J Prev Med. 2018;9(1):78.
14. Hong AR, Kim SW. Effects of resistance exercise on bone health. Endocrinol Metabolism (Seoul Korea). 2018;33(4):435–44.
15. Chang X, Xu S, Zhang H. Regulation of bone health through physical exercise: mechanisms and types. Front Endocrinol (Lausanne). 2022;13:1029475.
16. Wang L, You X, Zhang L, Zhang C, Zou W. Mechanical regulation of bone remodeling. Bone Res. 2022;10(1):16.
17. Oniszczuk A, Kaczmarek A, Kaczmarek M, Ciałowicz M, Arslan E, Silva AF, Clemente FM, Murawska-Ciałowicz E. Sclerostin as a biomarker of physical exercise in osteoporosis: A narrative review. Front Endocrinol (Lausanne). 2022;13:954895.
18. Bae S, Lee S, Park H, Ju Y, Min SK, Cho J, Kim H, Ha YC, Rhee Y, Kim YP, Kim C. Position statement: exercise guidelines for osteoporosis management and fall prevention in osteoporosis patients. J Bone Metabolism. 2023;30(2):149–65.
19. O'Bryan SJ, Giuliano C, Woessner MN, Vogrin S, Smith C, Duque G, Levinger I. Progressive Resistance Training for Concomitant Increases in Muscle Strength and Bone Mineral Density in Older Adults: A Systematic Review and Meta-Analysis. Sports medicine (Auckland, N.Z.). 2022;52(8):1939–1960.
20. Kistler-Fischbacher M, Yong JS, Weeks BK, Beck BR. A comparison of bone-Targeted exercise with and without antiresorptive bone medication to reduce indices of fracture risk in postmenopausal women with low bone mass: the MEDEX-OP randomized controlled trial. J Bone Mineral Research: Official J Am Soc Bone Mineral Res. 2021;36(9):1680–93.
21. Sterne JAC, Savović J, Page MJ, Elbers RG, Blencowe NS, Boutron I, Cates CJ, Cheng HY, Corbett MS, Eldridge SM, Emberson JR, Hernán MA, Hopewell S, Hróbjartsson A, Junqueira DR, Jüni P, Kirkham JJ, Lasserson T, Li T, McAleenan A, Reeves BC, Shepperd S, Shrier I, Stewart LA, Tilling K, White IR, Whiting PF, Higgins JPT. RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ (Clinical research ed.) 2019;366:l4898.
22. Bemben DA, Fetters NL, Bemben MG, Nabavi N, Koh ET. Musculoskeletal responses to high- and low-intensity resistance training in early postmenopausal women. Med Sci Sports Exerc. 2000;32(11):1949–57.
23. Bemben DA, Palmer IJ, Bemben MG, Knehans AW. Effects of combined whole-body vibration and resistance training on muscular strength and bone metabolism in postmenopausal women. Bone. 2010;47(3):650–6.
24. Maddalozzo GF, Widrick JJ, Cardinal BJ, Winters-Stone KM, Hoffman MA, Snow CM. The effects of hormone replacement therapy and resistance training on spine bone mineral density in early postmenopausal women. Bone. 2007;40(5):1244–51.
25. Nelson ME, Fiatarone MA, Morganti CM, Trice I, Greenberg RA, Evans WJ. Effects of high-intensity strength training on multiple risk factors for osteoporotic fractures. A randomized controlled trial. JAMA. 1994;272(24):1909–14.
26. Pruitt LA, Taaffe DR, Marcus R. Effects of a one-year high-intensity versus low-intensity resistance training program on bone mineral density in older women. J Bone Mineral Research: Official J Am Soc Bone Mineral Res. 1995;10(11):1788–95.
27. Bocalini DS, Serra AJ, dos Santos L, Murad N, Levy RF. Strength training preserves the bone mineral density of postmenopausal women without hormone replacement therapy. J Aging Health. 2009;21(3):519–27.
28. Bocalini DS, Serra AJ, Dos Santos L. Moderate resistive training maintains bone mineral density and improves functional fitness in postmenopausal women. Journal of aging research. 2010;2010:760818.
29. Chilibeck PD, Davison KS, Whiting SJ, Suzuki Y, Janzen CL, Peloso P. The effect of strength training combined with bisphosphonate (etidronate) therapy on bone mineral, lean tissue, and fat mass in postmenopausal women. Can J Physiol Pharmacol. 2002;80(10):941–50.
30. Chuin A, Labonté M, Tessier D, Khalil A, Bobeuf F, Doyon CY, Rieth N, Dionne IJ. Effect of antioxidants combined to resistance training on BMD in elderly women: a pilot study. Osteoporos International: J Established as Result Cooperation between Eur Foundation Osteoporos Natl Osteoporos Foundation USA. 2009;20(7):1253–8.
31. Rhodes EC, Martin AD, Taunton JE, Donnelly M, Warren J, Elliot J. Effects of one year of resistance training on the relation between muscular strength and bone density in elderly women. Br J Sports Med. 2000;34(1):18–22.
32. Karinkanta S, Heinonen A, Sievänen H, Uusi-Rasi K, Pasanen M, Ojala K, Fogelholm M, Kannus P. A multi-component exercise regimen to prevent functional decline and bone fragility in home-dwelling elderly women: randomized, controlled trial. Osteoporos International: J Established as Result Cooperation between Eur Foundation Osteoporos Natl Osteoporos Foundation USA. 2007;18(4):453–62.
33. Marques EA, Wanderley F, Machado L, Sousa F, Viana JL, Moreira-Gonçalves D, Moreira P, Mota J, Carvalho J. Effects of resistance and aerobic exercise on

physical function, bone mineral density, OPG and RANKL in older women. Exp Gerontol. 2011;46(7):524–32.
34. Verschueren SM, Roelants M, Delecluse C, Swinnen S, Vanderschueren D, Boonen S. Effect of 6-month whole body vibration training on hip density, muscle strength, and postural control in postmenopausal women: a randomized controlled pilot study. J Bone Mineral Research: Official J Am Soc Bone Mineral Res. 2004;19(3):352–9.
35. Holubiac IS, Leuciuc FV. The role of the dual X-Ray absorptiometry investigation in the design of personalized training programs for women with postmenopausal osteopenia / osteoporosis. Balneo Prm Res J 2023;14(4).
36. Juesas A, Gargallo P, Gene-Morales J, Babiloni-López C, Saez-Berlanga A, Jiménez-Martínez P, Casaña J, Benitez-Martinez JC, Ramirez-Campillo R, Chulvi-Medrano I, Colado JC. Effects of Microfiltered Seawater Intake and Variable Resistance Training on Strength, Bone Health, Body Composition, and Quality of Life in Older Women: A 32-Week Randomized, Double-Blinded, Placebo-Controlled Trial. Int J Environ Res Public Health 2023;20(6).
37. Eslamipour F, Gheitasi M, Hovanloo F, Yaghoubitajani Z. High versus Low-Intensity resistance training on bone mineral density and content acquisition by postmenopausal women with osteopenia: A randomized controlled trial. Med J Islamic Repub Iran. 2023;37:126–126.
38. Abdul-Al O, Zunquin G, El Hage R. Effects of two types of resistance training modalities (hypertrophy vs. contrast training) on bone parameters in a group of healthy elderly women. J Clin Densitometry. 2024;27(4).
39. Borde R, Hortobágyi T, Granacher U. Dose-Response relationships of resistance training in healthy old adults: A systematic review and Meta-Analysis. Sports Med. 2015;45(12):1693–720.
40. Huang F, Wang Y, Liu J, Cheng Y, Zhang X, Jiang H. Asperuloside alleviates osteoporosis by promoting autophagy and regulating Nrf2 activation. J Orthop Surg Res. 2024;19(1):855.
41. Andersen M, Andresen AK, Hartvigsen J, Hermann AP, Sørensen J, Carreon LY. Vertebroplasty for painful osteoporotic vertebral compression fractures: a protocol for a single-center doubled-blind randomized sham-controlled clinical trial. VOPE2. J Orthop Surg Res. 2024;19(1):813.
42. Shen L, Yang H, Zhou F, Jiang T, Jiang Z. Risk factors of short-term residual low back pain after PKP for the first thoracolumbar osteoporotic vertebral compression fracture. J Orthop Surg Res. 2024;19(1):792.
43. Leeyaphan J, Rojjananukulpong K, Intarasompun P, Peerakul Y. Simple clinical predictors for making directive decisions in osteoporosis screening for women: a cross-sectional study. J Orthop Surg Res. 2024;19(1):789.
44. Dror AD, Virk K, Lee K, Gerston A, Prakash A, Abbott MJ, Jaque SV, Sumida KD. Resistance training threshold for elevating bone mineral density in growing female rats. Int J Sports Med. 2018;39(5):382–9.
45. Stunes AK, Erben RG, Schüler C, Eriksen EF, Tice M, Vashishth D, Syversen U, Mosti MP. Skeletal effects of plyometric exercise and Metformin in ovariectomized rats. Bone. 2020;132:115193.
46. Kistler-Fischbacher M, Weeks BK, Beck BR. The effect of exercise intensity on bone in postmenopausal women (part 2): A meta-analysis. Bone. 2021;143:115697.
47. Howe TE, Shea B, Dawson LJ, Downie F, Murray A, Ross C, Harbour RT, Caldwell LM, Creed G. Exercise for preventing and treating osteoporosis in postmenopausal women. Cochrane Database Syst Rev. 2011;(7):Cd000333.
48. Zaki ME. Effects of whole body vibration and resistance training on bone mineral density and anthropometry in obese postmenopausal women. Journal of osteoporosis. 2014;2014:702589.
49. Kemmler W, Shojaa M, Kohl M, von Stengel S. Effects of different types of exercise on bone mineral density in postmenopausal women: A systematic review and Meta-analysis. Calcif Tissue Int. 2020;107(5):409–39.
50. Wang Z, Zan X, Li Y, Lu Y, Xia Y, Pan X. Comparative efficacy different resistance training protocols on bone mineral density in postmenopausal women: A systematic review and network meta-analysis. Front Physiol. 2023;14:1105303.
51. Kumar S, Smith C, Clifton-Bligh RJ, Beck BR, Girgis CM. Exercise for postmenopausal bone Health - Can we Raise the bar?? Curr Osteoporos Rep. 2025;23(1):20.
52. Vainionpää A, Korpelainen R, Vihriälä E, Rinta-Paavola A, Leppäluoto J, Jämsä T. Intensity of exercise is associated with bone density change in premenopausal women. Osteoporos International: J Established as Result Cooperation between Eur Foundation Osteoporos Natl Osteoporos Foundation USA. 2006;17(3):455–63.
53. Borba-Pinheiro CJ, Dantas EH, Vale RG, Drigo AJ, Carvalho MC, Tonini T, Meza EI, Figueiredo NM. Resistance training programs on bone related variables and functional independence of postmenopausal women in Pharmacological treatment: A randomized controlled trial. Arch Gerontol Geriatr. 2016;65:36–44.
54. Kistler-Fischbacher M, Weeks BK, Beck BR. The effect of exercise intensity on bone in postmenopausal women (part 1): A systematic review. Bone. 2021;143:115696.
55. Fuchs RK, Bauer JJ, Snow CM. Jumping improves hip and lumbar spine bone mass in prepubescent children: a randomized controlled trial. J Bone Mineral Research: Official J Am Soc Bone Mineral Res. 2001;16(1):148–56.

## Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.