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Review Article

Effectiveness of different exercise types for improving bone mineral density in adults: A pairwise, network, and dose-response meta-analysis of 162 randomized controlled trials☆

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ABSTRACT

Background: Comparative effectiveness of exercise modalities across skeletal sites and the dose-response pattern for bone mineral density (BMD) remain incompletely characterized. This review aimed to compare exercise modalities across six skeletal sites and to explore whether MET-min/week could describe a dose-response relationship between exercise exposure and BMD change.

Methods: We conducted a systematic review and meta-analysis of RCTs (PROSPERO: CRD420261345811), searching four databases to March 2026. Three complementary frameworks were applied: three-level pairwise meta-analysis with robust variance estimation, Bayesian network meta-analysis (NMA) with prespecified vague priors and SUCRA rankings, and exploratory dose-response model-based NMA using restricted cubic spline modelling of MET-min/week. Methodological quality was assessed using ROBUST-RCT, GRADE, and an NMA-specific certainty assessment considering intransitivity and incoherence.

Results: We included 162 RCTs (10,475 participants; age range, 18–81.6 years). Pairwise GRADE certainty ranged from high (femoral neck) to very low (total hip). Significant pooled effects were observed at five of six sites: lumbar spine (Hedges' g = 0.22), femoral neck (g = 0.28), Ward's triangle (g = 0.23), trochanter (g = 0.15), and total body (g = 0.26). NMA suggested site-specific ranking patterns, but credible intervals were often wide and NMA certainty was commonly limited by imprecision, heterogeneity, and sparse direct evidence. Dose-response analyses suggested an overall peak near 1100 MET-min/week for lumbar spine BMD, but agent-specific optima, especially AT+RT at 1800 MET-min/week, were boundary-sensitive and exploratory.

Conclusion: Exercise is associated with small-to-moderate, site-specific improvements in BMD across adulthood. Modality rankings and dose-response estimates should be interpreted as hypothesis-generating rather than definitive prescriptions, particularly where direct evidence was sparse or certainty was low.

1. Introduction

Osteoporosis, characterized by reduced bone mineral density (BMD) and microarchitectural deterioration of bone tissue, is a major global public health concern that markedly increases susceptibility to fragility fractures [1,2]. Worldwide, approximately one in three women and one in five men over the age of 50 will sustain an osteoporosis-related fracture during their remaining lifetime [3]. Data from the Global

Abbreviations: AE, Aquatic Exercise; AT, Aerobic Training; AT + RT, Combined Aerobic and Resistance Training; CE, Combined Exercise; CON, Control; IE, Impact Exercise; MBE, Mind-Body Exercise; RT, Resistance Training; RT + IE, Resistance Training Plus Impact Exercise; TCE, Traditional Chinese Exercise; WBV, Whole Body Vibration.

☆ Registration: PROSPERO CRD420261345811

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Burden of Disease Study 2019 revealed that deaths attributable to low BMD more than doubled from 1990 to 2019, with disability-adjusted life years rising by approximately 94% over the same period [4,5]. With accelerating population aging, the annual incidence of hip fractures alone is projected to nearly double by 2050, imposing a substantial and growing burden on healthcare systems worldwide [6]. Notably, bone loss is not confined to postmenopausal women but also affects aging men, individuals with chronic comorbidities, and those exposed to prolonged physical inactivity, underscoring the need for effective population-wide preventive strategies across the adult lifespan [7,8].

Among non-pharmacological strategies for counteracting bone loss, physical exercise is widely regarded as the most accessible and cost-effective intervention. Physically active individuals consistently maintain higher BMD and experience fewer fragility fractures than their sedentary counterparts [9,10]. The underlying rationale is that bone is a mechanosensitive tissue whose mass and architecture adapt proportionally to habitual loading demands: when mechanical stimuli exceed customary levels, a net anabolic skeletal response is initiated; when loading is chronically insufficient, resorption predominates and mineral loss accelerates [11,12]. Importantly, the osteogenic potential of exercise depends not solely on load magnitude but also on the rate, frequency, and novelty of the applied forces, suggesting that different exercise modalities may confer differential benefits across skeletal sites [13,14].

Over the past two decades, a substantial body of randomized controlled trials (RCTs) has examined the effects of diverse exercise modalities on BMD at clinically relevant skeletal sites, including resistance training (RT), aerobic training (AT), impact exercise (IE), combined exercise (CE), and mind-body exercise [15–20]. However, results across individual trials and existing meta-analyses have been inconsistent, with reported effect sizes varying from negligible to moderate depending on the exercise type, skeletal site, and population studied [21,22]. Several systematic reviews have sought to clarify these discrepancies, yet critical limitations persist: most syntheses have focused exclusively on postmenopausal women, restricting generalizability to the broader adult population [23–25]; the majority relied on conventional pairwise methods that compare only two interventions at a time and cannot simultaneously rank multiple modalities [26,27]; and although a small number of network meta-analyses have recently emerged, these have generally been confined to specific subpopulations or narrow exercise categories [28,29]. Moreover, the dose-response relationship between exercise dose and BMD outcomes remains poorly defined, with current clinical guidelines lacking sufficient quantitative evidence to specify optimal dosing thresholds or identify potential plateau effects [30,31]. Collectively, these gaps leave a fundamental question unresolved: which exercise types are most osteogenic at specific skeletal sites, and what dose is required to maximize benefit?

To address these gaps, we conducted a comprehensive systematic review and meta-analysis of RCTs examining the effects of different exercise types on BMD in adults. The primary objective was to evaluate and rank the comparative effectiveness of exercise modalities across six skeletal sites (lumbar spine, femoral neck, Ward's triangle, trochanter, total hip, and total body) through Bayesian network meta-analysis, integrating both direct and indirect evidence to provide probabilistic treatment rankings. As secondary analyses, three-level pairwise meta-analyses with robust variance estimation were performed to quantify pooled effect sizes while accounting for the dependency among multiple outcomes nested within studies, and nonlinear dose-response modelling based on metabolic equivalents of task minutes per week (METs-min/week) was conducted to identify the optimal exercise volume for maximizing osteogenic benefit and to examine potential plateau effects.

2. Methods

This systematic review and meta-analysis was conducted and reported in accordance with the PRISMA-NMA extension statement [32] and followed the methodological guidance outlined in the Cochrane Handbook for Systematic Reviews of Interventions [33]. The review protocol was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO; registration number: CRD420261345811).

2.1. Search strategy

A systematic literature search was conducted across four electronic databases — PubMed, Embase, the Cochrane Central Register of Controlled Trials (CENTRAL), and Web of Science — from database inception to March 1, 2026, restricted to English-language publications. The search strategy employed Boolean operators combining Medical Subject Headings (MeSH) terms with free-text keywords. The primary search strategy was developed in PubMed, informed by the search strategies of relevant prior systematic reviews and meta-analyses in this field [21], and subsequently adapted to the syntax and controlled vocabulary of each remaining database. To ensure comprehensive retrieval, gray literature sources including OpenGrey, the WHO International Clinical Trials Registry Platform (ICTRP), and ClinicalTrials.gov were also searched. Previously published systematic reviews and meta-analyses were screened for additional eligible references, supplemented by searches in Google Scholar and manual examination of the reference lists of all included studies. The full search strategies for all databases are presented in Supplementary 2.

2.2. Eligibility criteria

Studies were eligible for inclusion if they met all of the following criteria: (i) participants were adults (aged $\geq$18 years) of either sex, regardless of health status or clinical subgroup; (ii) the intervention comprised any structured exercise program, whether delivered alone or alongside a co-intervention applied equally to both groups (e.g., exercise plus calcium supplementation versus calcium supplementation alone), ensuring that exercise represented the sole differentiating variable between conditions; (iii) the comparator was a non-exercise control group, defined as no intervention, usual care, or placebo/sham exercise; (iv) at least one site-specific BMD outcome (g/cm^2) measured by dual-energy X-ray absorptiometry (DXA), the recognized reference standard for BMD assessment in osteoporosis diagnosis and clinical trials [34], was reported at the lumbar spine, femoral neck, Ward's triangle, trochanter, total hip, or total body; and (v) the study design was a randomized controlled trial (RCT).

Studies were excluded if: (i) participants were pregnant women; or (ii) a within-participant unilateral design was employed, in which one limb served as the exercise condition and the contralateral limb as the control, as this design precludes valid systemic between-condition comparisons of bone adaptation.

2.3. Study selection

All identified records were imported into EndNote 21 (Clarivate Analytics, Philadelphia, PA, USA) for deduplication and management of references. Following removal of duplicates and clearly ineligible records through automated filtering, the remaining records underwent title and abstract screening by two independent reviewers against the predefined eligibility criteria. Full-text articles of all potentially eligible records were subsequently retrieved and independently assessed by the same two reviewers. Disagreements at both screening stages were resolved through discussion and consensus; where agreement could not be reached, a third reviewer served as arbiter. The complete study selection process is presented as a PRISMA 2020 flow diagram.

2.4. Data extraction

Two reviewers (H.F. and Z.W.X.) independently extracted data using

a pre-piloted form developed in Microsoft Excel (Microsoft Corporation, Redmond, WA, USA); graphical data were digitized with WebPlotDigitizer (version 4.8; Automeris LLC, Austin, TX, USA; https://automeris.io/WebPlotDigitizer/). A third reviewer (Y.W.) independently cross-checked all entries. The artificial intelligence tool previously mentioned was ChatGPT (OpenAI, GPT-4o class model, accessed in March 2026), which was used only as a clerical aid to flag possible inconsistencies in copied numerical fields and was not used for eligibility decisions, data extraction, statistical analysis, or adjudication. All flagged items were verified manually against the source articles by human reviewers. Because the tool only flagged candidate discrepancies for subsequent manual verification against the source, it had no effect on the extracted data.

For each included trial, study-level characteristics, participant demographics, and intervention parameters were systematically recorded, with all exercise conditions classified according to a unified coding framework. The primary outcome was lumbar spine BMD (g/cm^2) measured by DXA; femoral neck, Ward's triangle, trochanter, total hip, and total body BMD constituted five prespecified secondary outcomes. Where SDs were unavailable, they were imputed from other reported statistics in accordance with the Cochrane Handbook. Detailed conversion procedures are reported in Supplementary 3.

2.5. Data coding

All exercise interventions were classified into one of ten predefined mutually exclusive categories before analysis, as defined in Supplementary 1. Classification was based on the dominant osteogenic stimulus and the description of the intervention protocol: aquatic exercise (AE), aerobic training (AT), combined aerobic and resistance training (AT+RT), combined exercise (CE), impact exercise (IE), mind-body exercise (MBE), resistance training (RT), resistance training plus impact exercise (RT + IE), traditional Chinese exercise (TCE), and whole-body vibration (WBV). Participant sex, menopausal status, comorbidity, and supervision were coded at the study-arm level from reported eligibility criteria, baseline descriptions, or target population. Menopausal status was therefore a study-level classification rather than an individual participant-level inference; when status could not be determined from the article, it was coded as not specified.

Exercise dose was operationalized as MET-min/week, calculated as assigned MET value multiplied by session duration and weekly session frequency. MET values were assigned according to exercise type and reported intensity using the 2024 Adult Compendium of Physical Activities [37] and American College of Sports Medicine guidance [38], as detailed in Supplementary 1. When intensity was not reported, a conservative default MET value for the corresponding activity category was used and flagged in the audit table; this occurred in 67 of 162 studies. Frequency was missing in 3 studies and session duration in 14 studies; arms lacking derivable frequency or duration were not used for quantitative MET-min/week dose-response modelling. For resistance training, session duration was taken directly from the report when available; it was not reconstructed from sets, repetitions, or exercise number because rest intervals and tempo were inconsistently reported. MET-min/week was used as a pragmatic cross-modality exposure metric, but it does not capture loading rate, impact magnitude, directionality, rest intervals, or progressive overload, and dose-response findings were therefore interpreted as exploratory.

2.6. Risk of bias and quality of evidence assessment

The methodological quality of each included trial was independently assessed by two reviewers using the ROBUST-RCT tool [39], which evaluates six core domains: random sequence generation, allocation concealment, blinding of participants, blinding of healthcare providers, blinding of outcome assessors, and missing outcome data. Pairwise certainty was appraised using the GRADE approach [40]. For the NMA, we additionally summarized certainty using an NMA-specific framework aligned with GRADE NMA/CINeMA principles, considering within-study bias, indirectness/transitivity, incoherence, imprecision, heterogeneity, and reporting bias. These judgments were used to temper treatment-ranking conclusions rather than to make strong superiority claims.

2.7. Statistical analysis

All statistical analyses were performed in R (version 4.3.0; R Core Team, Vienna, Austria), incorporating three complementary analytical frameworks: three-level pairwise meta-analysis, Bayesian network meta-analysis, and dose-response model-based network meta-analysis (MBNMA).

2.7.1. Three-level pairwise meta-analysis

Three-level random-effects meta-analyses were conducted using the metafor package [41] with restricted maximum likelihood (REML) estimation, with effect sizes expressed as Hedges' g with small-sample correction. As no consensus MCID for BMD exists, magnitudes were interpreted using Cohen's benchmarks (small 0.2, moderate 0.5, large $\geq$0.8) [42] Models were fitted by nesting effect sizes within studies to account for the dependency structure arising from multiple outcomes reported within the same trial [43] as a statistical reference only, not as thresholds of clinical importance. Robust variance estimation with Satterthwaite small-sample corrections was implemented using the clubSandwich package [44]. An assumed within-study correlation of $r = 0.6$ was applied to construct the variance-covariance matrix, with sensitivity analyses conducted under $r = 0.4$ and $r = 0.8$ to evaluate result robustness [45]. Heterogeneity was decomposed into within-study (Level 2) and between-study (Level 3) variance components using I^2 statistics, and the necessity of the three-level structure was evaluated using likelihood ratio tests. Post hoc statistical power was calculated for each outcome. Publication bias was assessed using multilevel Egger's regression, supplemented by funnel plots and sunset funnel plots. Influential studies were identified using Cook's distance, standardized residuals, and hat values, and pooled estimates were re-examined after their removal to confirm result stability. Subgroup analyses were conducted for thirteen prespecified moderator variables using the omnibus test of moderators (Q_M); subgroup levels with fewer than three effect sizes were excluded from analysis.

2.7.2. Bayesian network meta-analysis

Bayesian NMA was performed using the gemtc package via Markov chain Monte Carlo (MCMC) sampling implemented in JAGS, with three chains, 20,000 iterations, 10,000 burn-in, and a thinning interval of 10. Random-effects consistency models were fitted for each of the six BMD outcomes. Vague normal priors were assigned to treatment effects (normal distribution with mean 0 and precision 0.0001), and a vague uniform prior was assigned to the between-study standard deviation (0 to 5). Convergence was confirmed by Gelman-Rubin statistics (R-hat $<$1.01) and visual inspection of trace plots. Global consistency was evaluated by comparing consistency and unrelated mean effects (UME) models using DIC, and local inconsistency was assessed with node-splitting. Transitivity was assessed by comparing key study-level effect modifiers, including menopausal status, age group, intervention duration, frequency, supervision, comorbidity, and exercise dose variables, across treatment nodes.

2.7.3. Dose-response model-based network meta-analysis

Dose-response MBNMA was performed using the MBNMAdose package [47,48] as a supplementary, exploratory analysis for lumbar spine BMD. Network connectivity, consistency, and transitivity were assessed before modelling. Three dose-response functions were compared: Emax, restricted cubic spline (RCS), and quadratic polynomial models. Because MET-min/week combines metabolic cost,

duration, and frequency but does not directly represent bone-specific loading rate or strain magnitude, the model was used to explore broad exposure-response patterns rather than to define a clinically prescriptive optimal dose.

3. Results

3.1. Study selection and characteristics

A total of 43,646 records were identified from four electronic databases, and following removal of 9918 duplicates, sequential title-abstract and full-text screening, and supplementation with 46 records from gray literature and manual searching, 162 RCTs enrolling 10,475 participants (exercise: $n = 5826$; control: $n = 4649$) were included in the final analysis, as illustrated in Fig. 1; inter-rater reliability across both screening stages was excellent (ICC = 0.88). The primary outcome was lumbar spine BMD, with femoral neck, Ward's triangle, trochanter, total hip, and total body BMD constituting the five prespecified secondary outcomes, all measured by DXA (g/cm^2). Participant mean ages ranged from 18 to 81.6 years, with postmenopausal women constituting the largest subgroup, followed by mixed-sex cohorts, non-postmenopausal females, and male-only samples. Approximately one-third of trials enrolled participants with clinically relevant comorbidities, most commonly osteoporosis, breast cancer survivorship, and sarcopenia. Adverse events were reported in 46 trials and were predominantly minor in nature; serious exercise-attributable events were rare, supporting the overall safety of structured exercise interventions for bone health outcomes. Detailed characteristics of all included studies are provided in Supplementary 4.

3.2. Risk of bias and quality of evidence

Risk of bias ratings across the 162 included RCTs are summarized in Fig. 2. Random sequence generation and blinding of outcome assessors were satisfactory in the majority of trials (definitely or probably low risk: 87% and 91%, respectively), whereas allocation concealment (high risk: 29%) and blinding of participants (high risk: 56%) were more frequently compromised, the latter reflecting the structural difficulty of masking exercise allocation. Pairwise GRADE certainty ranged from high for femoral neck to very low for total hip. NMA certainty was generally moderate to low for well-connected comparisons and low to very low for sparse or inconsistent contrasts, so all ranking-based conclusions were framed cautiously.

3.3. Pairwise meta-analysis results

Likelihood ratio tests confirmed the necessity of the three-level structure for the lumbar spine, femoral neck, and total hip outcomes ($p < 0.05$). Exercise interventions produced statistically significant positive effects on lumbar spine (Hedges' g = 0.22, 95% CI [0.15, 0.29], $p < 0.001$; k = 182, $N = 9260$), femoral neck (Hedges' g = 0.28 [0.18, 0.38], p < 0.001; k = 147, $N = 7257$), Ward's triangle (Hedges' g = 0.23 [0.12, 0.35], p < 0.001; k = 42, $N = 1553$), trochanter (Hedges' g = 0.15 [0.01, 0.29], $p = 0.03$; k = 78, $N = 4072$), and total body BMD (Hedges' g = 0.26 [0.09, 0.44], $p = 0.004$; k = 38, $N = 1386$); see Fig. 3. No significant effect was observed for total hip BMD (Hedges' g = 0.05 [−0.07, 0.18], $p = 0.40$; post hoc power = 18%). Results were robust to sensitivity analyses across assumed within-study correlations and influential study removal; significant funnel plot asymmetry was detected only for the lumbar spine ($p < 0.001$). Subgroup analyses across thirteen moderators are detailed in Supplementary 6; effects were broadly consistent across subgroups, with supervised exercise, higher training frequency (≥3 sessions/week), and longer intervention duration (≥6 months) associated with larger effects at the lumbar spine and femoral neck. Detailed results for all analyses are reported in Supplementary 6.

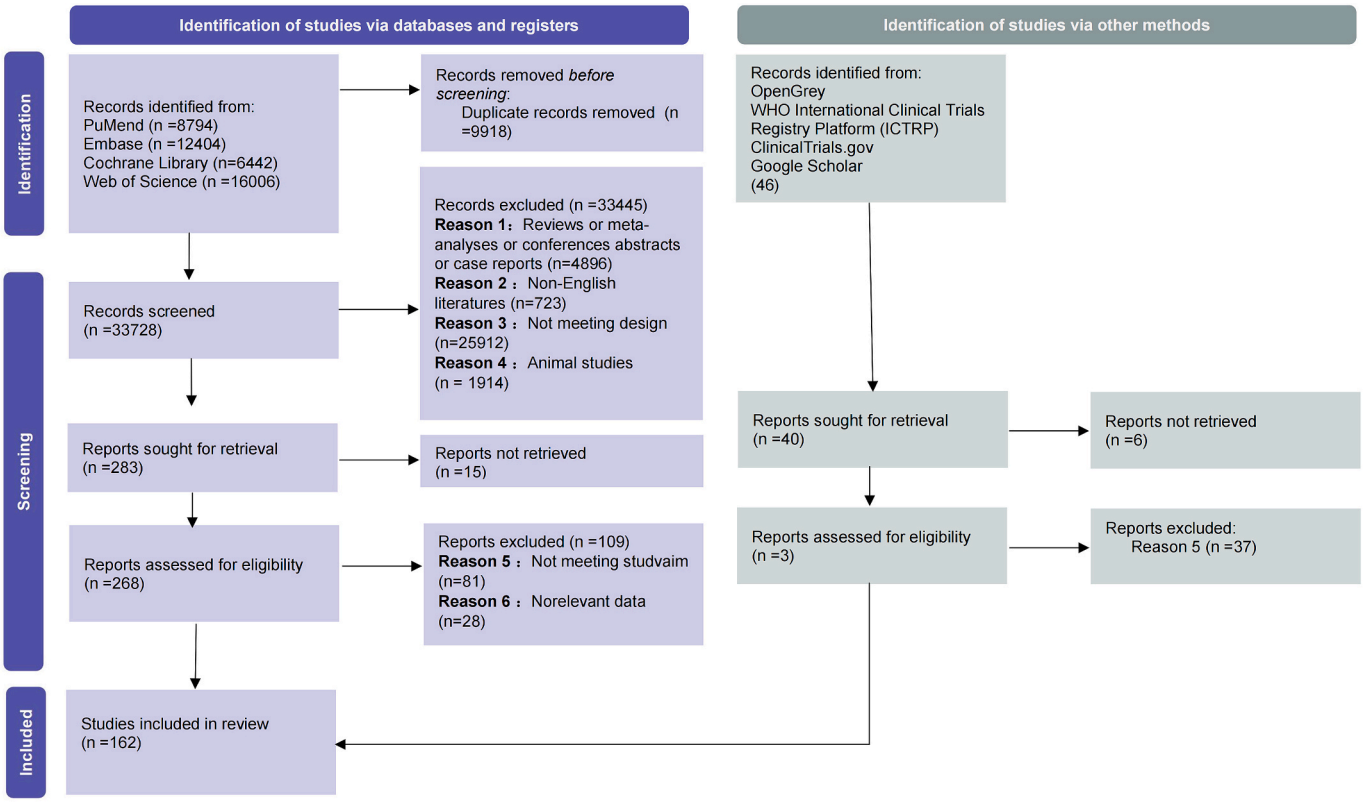

Fig. 1. PRISMA flow diagram of study selection.

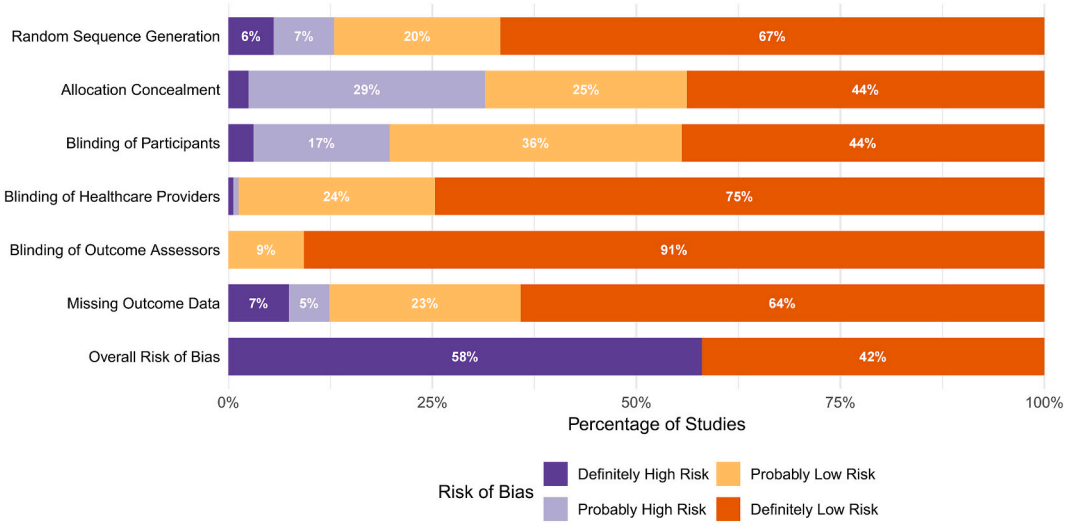

Fig. 2. Risk of bias summary of included trials.

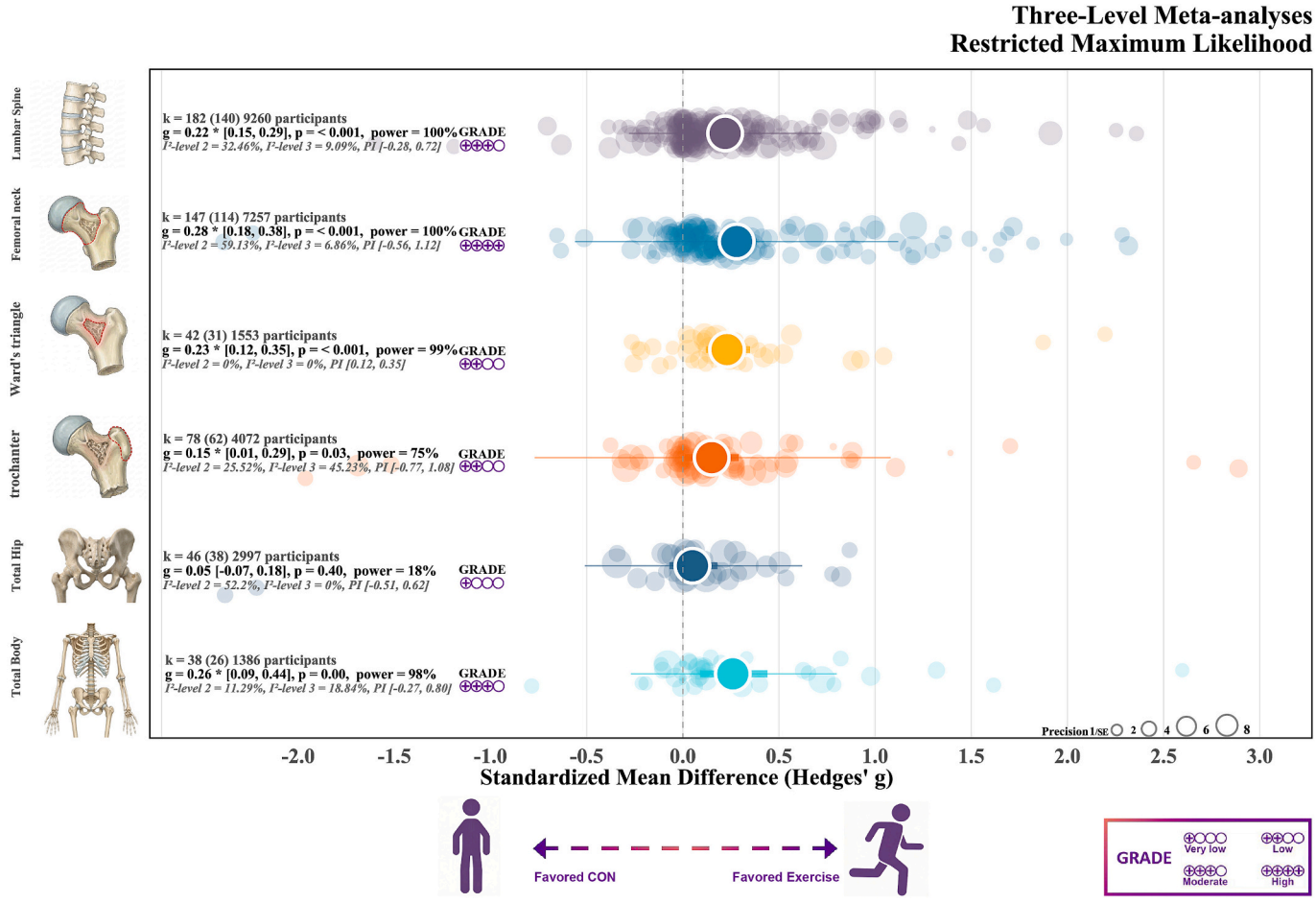

Fig. 3. Three-level meta-analysis results for six BMD outcomes.

3.4. *Network meta-analysis results*

Global consistency tests generally supported the consistency models, although Ward's triangle showed poorer fit for the consistency model and was interpreted cautiously. Node-splitting analyses identified local inconsistency at the femoral neck for AE versus CON and AE versus RT, and WBV was excluded from the Ward's triangle network because of substantial inconsistency in preliminary analyses. Full global and local inconsistency results, including comparison-level estimates, are provided in Supplementary 8 and Supplementary 9.

For lumbar spine BMD, compared with control, AT+RT (MD = 0.047, 95% CrI [0.022, 0.073]), TCE (MD = 0.044, 95% CrI [0.016, 0.071]), and RT (MD = 0.022, 95% CrI [0.010, 0.034]) had 95% CrIs excluding zero. No active head-to-head comparison showed clear

separation. SUCRA rankings placed AT+RT (87.05%) and TCE (83.37%) highest, followed by RT (56.63%) and CE (54.56%); these rankings were interpreted alongside the overlapping CrIs and certainty assessment (Fig. 4, Table 1).

For femoral neck BMD, AE, RT, IE, AT, and AT+RT had 95% CrIs excluding zero compared with control. However, no active modality clearly outperformed another, and local inconsistency was detected for AE-related comparisons. SUCRA ranked AE highest (87.99%), followed by RT (71.56%), IE (71.08%), and AT (66.67%), but the AE ranking was treated as uncertain because it was driven by sparse and partially inconsistent evidence.

For Ward's triangle BMD, AT, TCE, RT, and IE had 95% CrIs excluding zero compared with control. Some active comparisons favored AT or TCE, but the network showed evidence of global inconsistency and WBV was removed during preliminary inconsistency checks. SUCRA ranked AT (82.04%) and CE (70.66%) highest, followed by TCE (68.00%) and MBE (60.09%); these ranks should be viewed as exploratory.

For trochanter BMD, no intervention had a 95% CrI excluding zero compared with control, and active head-to-head comparisons were imprecise. SUCRA rankings favored AE (79.05%), CE (78.81%), and TCE (77.18%), but the wide intervals and sparse direct evidence indicate substantial uncertainty.

For total hip BMD, no intervention had a 95% CrI excluding zero compared with control. The only active head-to-head contrast with a 95% CrI excluding zero favored RT over AT (MD = 0.013, 95% CrI [0.002, 0.022]). SUCRA rankings placed RT (67.88%) and RT + IE (67.56%) highest, but the low pairwise power and low certainty at this site limit clinical interpretation.

For total body BMD, IE and RT had 95% CrIs excluding zero compared with control, whereas AT estimates were small and sensitive to contrast orientation. A coding audit confirmed that AT arms were correctly entered, but the apparent unfavorable AT ranking was driven by small absolute changes, sparse direct comparisons, and indirect evidence. We therefore did not interpret AT as harmful. SUCRA ranked IE highest (84.04%), followed by RT (66.12%) and MBE (64.79%); these rankings should be treated as exploratory.

3.5. Dose-response meta-analysis results

Dose-response MBNMA was conducted as a supplementary analysis of lumbar spine BMD. The analysis included 206 dose-specific treatment arms and 82 unique dose-treatment combinations nested within 10 exercise agents. The RCS model provided the best fit (DIC = −1880.4), outperforming the Emax and quadratic models. The overall dose-response curve suggested an inverted U-shaped pattern, with the largest predicted effect near 1100 MET-min/week (SMD = 0.48, 95% CrI [0.28, 0.77]). Agent-specific curves suggested possible peaks for IE and RT within observed dose ranges, whereas the AT+RT peak at 1800 MET-min/week occurred at the upper boundary and was supported by a single boundary dose arm. Two node-splitting comparisons showed inconsistency (RT_450 vs AT_800 and AT+RT_1250 vs AT_1350). These dose-response findings should therefore be interpreted as exploratory and hypothesis-generating rather than as definitive optimal prescriptions.

4. Discussion

4.1. Principal findings

This comprehensive meta-analysis integrated 162 RCTs, 10,475 participants, three complementary analytical frameworks, and six skeletal sites. The main contribution is not that one exercise modality is universally superior, but that exercise effects appear site-specific and that comparative rankings are highly dependent on network connectivity, certainty, and skeletal region. Pairwise analyses showed small-to-moderate positive effects at five of six sites, whereas NMA suggested possible site-specific ranking patterns: AT+RT and TCE for lumbar spine, RT and possibly AE for femoral neck, AT/TCE-related modalities for Ward's triangle, and IE/RT for total body BMD. Because several CrIs overlapped and many ranking probabilities were based on sparse direct evidence, these comparative findings are best interpreted as exploratory. The dose-response analysis adds a further hypothesis-generating observation: lumbar spine BMD may respond nonlinearly to exercise volume, with no evidence that benefit increases indefinitely with higher MET-min/week.

4.2. Site-specific exercise effects and mechanistic underpinnings

The significant pooled effect at the lumbar spine (Hedges' g = 0.22, 95% CI [0.15, 0.29]) is consistent with prior meta-analyses restricted to postmenopausal women [50,51], and the present analysis confirms that

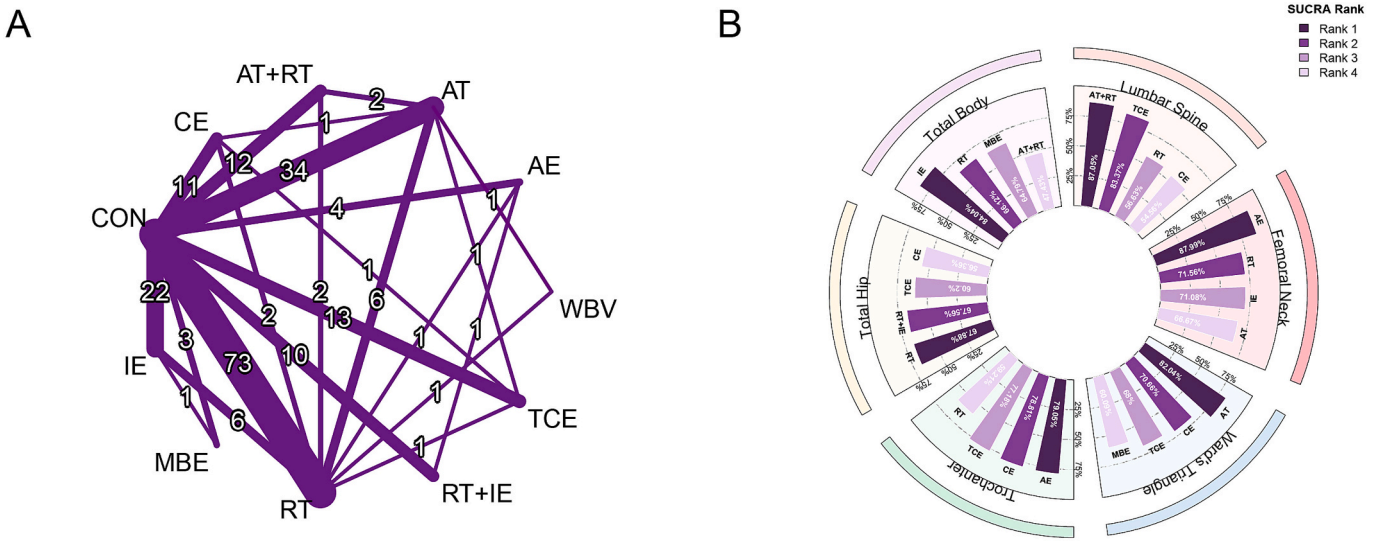

Fig. 4. Network geometry and SUCRA rankings for exercise interventions on BMD. (A) Network plot illustrating the evidence structure across ten exercise modalities and control; node connections represent direct comparisons, with line thickness proportional to the number of contributing studies. (B) Circular bar chart displaying SUCRA rankings of the top four interventions across six skeletal sites, with longer bars indicating higher probability of being the most effective intervention.

Table 1
Lumbar spine BMD pairwise and network meta-analysis comparison matrix.

AT+RT	—	—	—	—	—	—	—	—	—	0.01 [-1.00, 1.02]
0.004 (-0.034, 0.041)	TCE	—	—	—	—	—	—	—	—	—
0.024 (-0.014, 0.062)	0.020 (-0.018, 0.058)	CE	—	—	—	—	—	—	—	0.28 [-0.08, 0.63]
0.026 (-0.002, 0.053)	0.022 (-0.007, 0.052)	0.002 (-0.029, 0.032)	RT	—	—	—	—	—	—	**0.16*** [0.07, 0.25]
0.026 (-0.017, 0.068)	0.022 (-0.022, 0.066)	0.002 (-0.043, 0.047)	0.000 (-0.036, 0.037)	RT+IE	—	—	—	—	—	0.19 [-0.07, 0.44]
0.025 (-0.058, 0.110)	0.021 (-0.063, 0.107)	0.001 (-0.083, 0.086)	-0.001 (-0.081, 0.081)	-0.001 (-0.087, 0.087)	WBV	—	—	—	0.58 [-0.27, 1.42]	—
0.027 (-0.002, 0.056)	0.023 (-0.008, 0.055)	0.003 (-0.030, 0.036)	0.001 (-0.018, 0.021)	0.001 (-0.037, 0.039)	0.002 (-0.078, 0.081)	AT	—	—	—	0.15 [-0.34, 0.64]
0.032 (-0.001, 0.064)	0.028 (-0.006, 0.062)	0.008 (-0.027, 0.042)	0.006 (-0.016, 0.028)	0.006 (-0.034, 0.046)	0.007 (-0.077, 0.089)	0.005 (-0.021, 0.031)	IE	—	—	**0.61*** [0.21, 1.01]
0.036 (-0.035, 0.106)	0.032 (-0.040, 0.104)	0.012 (-0.060, 0.084)	0.010 (-0.057, 0.077)	0.010 (-0.063, 0.084)	0.011 (-0.093, 0.114)	0.009 (-0.059, 0.077)	0.004 (-0.064, 0.072)	MBE	—	—
0.041 (-0.014, 0.095)	0.037 (-0.019, 0.093)	0.017 (-0.039, 0.073)	0.015 (-0.034, 0.064)	0.015 (-0.040, 0.070)	0.016 (-0.078, 0.109)	0.014 (-0.037, 0.065)	0.009 (-0.043, 0.061)	0.005 (-0.077, 0.087)	AE	—
0.047 (0.022, 0.073)	**0.044** (0.016, 0.071)	0.023 (-0.005, 0.052)	**0.022** (0.010, 0.034)	0.022 (-0.013, 0.056)	0.022 (-0.058, 0.102)	**0.020** (0.004, 0.037)	0.016 (-0.004, 0.036)	0.011 (-0.004, 0.036)	0.007 (-0.042, 0.055)	CON

The upper triangle displays pairwise meta-analysis results (Hedges' g with 95% confidence intervals); the lower triangle displays network meta-analysis results (mean differences, MD g/cm^2, with 95% credible intervals, CrI). Color intensity reflects the magnitude of effect: deeper purple indicates larger effect size favoring the row intervention, and lighter shading indicates smaller or null effects. Diagonal cells identify each intervention. Asterisks (*) indicate comparisons whose interval excludes zero (95% CI for pairwise estimates and 95% CrI for Bayesian network estimates), rather than frequentist p values for Bayesian contrasts.

this osteogenic response generalizes to premenopausal females, aging men, and individuals with comorbidities such as osteoporosis, breast cancer survivorship, and sarcopenia. This broad population generalizability is further corroborated by the subgroup consistency observed across thirteen moderators examined in Supplementary 6, where exercise effects at both the lumbar spine and femoral neck remained directionally positive across sex, menopausal status, comorbidity type, and age group. Ward's triangle was the only outcome with zero between-study heterogeneity (I^2total = 0%, Q p = 0.479), indicating a remarkable consistency of the exercise-induced osteogenic response at this site across diverse populations and modalities, a finding not previously documented in the literature [52,53].

The larger pooled effect at the femoral neck (Hedges' g = 0.28, 95% CI [0.18, 0.38]) relative to the lumbar spine is mechanistically plausible. The proximal femur is predominantly cortical bone and is highly responsive to the dynamic strain magnitudes and strain rates generated during ambulatory and impact loading [14]. At the molecular level, mechanical loading suppresses osteocyte expression of the Wnt antagonist sclerostin, thereby releasing the inhibition of Wnt/β-catenin signaling in adjacent osteoblasts and driving new bone deposition; this mechanosensory regulation is finely tuned to the magnitude and rate of local strain. Concurrently, exercise-induced muscle contractions release myokines, including irisin, IGF-1, and IL-6, that act in an endocrine and paracrine manner on osteoblasts and osteoclasts to reinforce bone formation, constituting a musculoskeletal crosstalk axis that amplifies the direct mechanical osteogenic stimulus [54,55]. The substantially higher within-study heterogeneity at the femoral neck (I^2 L2 = 59.13%) compared with the lumbar spine (I^2 L2 = 32.46%) as detailed in Supplementary Table S6.2 likely reflects the greater sensitivity of this predominantly cortical site to variation in exercise intensity, modality specificity, and hormonal milieu across study arms.

The high NMA ranking of AE at the femoral neck should be interpreted cautiously. Although aquatic exercise reduces gravitational loading, a dedicated systematic review has suggested that water resistance and multidirectional movement may help preserve proximal femoral BMD in older adults [56]. In the present network, however, AE was supported by relatively few arms and local inconsistency was detected for AE versus CON and AE versus RT. The AE ranking may therefore reflect imprecision and indirect evidence as much as a true superiority signal, and it requires confirmation in adequately powered head-to-head trials.

The Ward's triangle findings are consistent with previous reviews suggesting that TCE, particularly Tai Chi, may benefit trabecular-dominant proximal femoral regions [57]. Mechanistically, repetitive weight shifting, single-leg stance, and controlled load transfer may provide relevant low-to-moderate osteogenic stimuli. However, the Ward's triangle network showed evidence of inconsistency, and SUCRA ranks for AT, CE, and TCE should not be read as definitive ordering. Similarly, the favorable total body ranking of IE is biologically plausible because impact loading engages multiple skeletal regions, but the

estimate remains dependent on a limited network and should be viewed as exploratory [58].

The absence of a significant pooled effect at the total hip (Hedges' g = 0.05, $p = 0.40$; post hoc power = 18%; Supplementary Table S6.2) should not be interpreted as evidence that exercise is ineffective at this region. Rather, total hip analyses were underpowered and showed substantial within-study variability. This is consistent with prior observations that null total hip findings in small or heterogeneous subsets should be interpreted cautiously [19]. The lumbar spine ranking of AT+RT is mechanistically plausible because combined training may deliver both high-magnitude muscle loading and repeated dynamic strain, but the superiority of AT+RT over other active modalities was not consistently established by head-to-head CrIs.

The exploratory dose-response analysis should be interpreted within important measurement constraints. MET-min/week enabled a common exposure scale across modalities, but it is a metabolic metric rather than a bone-specific loading metric. It cannot fully represent loading rate, ground-reaction force, strain direction, resistance intensity, rest intervals, progression, or exercise technique. Moreover, 67 studies lacked explicit intensity reporting, 3 lacked frequency, and 14 lacked session duration. The apparent AT+RT optimum at 1800 MET-min/week was located at the upper boundary of the observed AT+RT data and was supported by limited information. These results are therefore useful for generating trial-design hypotheses but should not be translated directly into clinical dose prescriptions.

4.3. Strengths and limitations

This study has several methodological strengths. The integration of pairwise, network, and dose-response approaches within a single review provides a broad comparative map of exercise and BMD outcomes. The three-level modelling approach, whose necessity was confirmed by LRT for three of six outcomes as shown in Supplementary Table S6.3, accounts for dependency among multiple effect sizes reported within the same trial, a source of statistical dependency that prior two-level syntheses in this field often did not fully address [43]. Inclusion of all adult populations extends the evidence base beyond the postmenopausal cohorts that dominate this literature [60]. The standardized MET-based dose framework enabled a transparent exploratory dose-response analysis, although its limitations are acknowledged below [61].

Several limitations warrant acknowledgement. First, blinding of participants and exercise providers was often infeasible, contributing to high overall risk of bias in many trials. Second, heterogeneity remained substantial at the femoral neck and trochanter despite moderator analyses. Third, NMA rankings were limited by sparse direct evidence, local inconsistency for selected contrasts, and low or very low certainty for several comparisons; therefore, all modality rankings should be considered exploratory. Fourth, the MET-min/week dose variable is a rough cross-modality exposure metric and does not capture bone-specific loading characteristics such as strain rate, impact magnitude, resistance load, rest intervals, or progressive overload. Missing or incomplete reporting of intensity, frequency, and session duration further reduced the clinical interpretability of dose-response analyses. Fifth, the available data did not permit a formal component network meta-analysis separating impact, resistance, balance, and aerobic components, which may be more clinically informative than broad modality labels. Finally, DXA-measured areal BMD does not capture bone geometry, cortical thickness, trabecular microarchitecture, or fracture outcomes.

5. Conclusion

This pairwise, network, and exploratory dose-response meta-analysis of 162 RCTs suggests that structured exercise is associated with small-to-moderate, site-specific improvements in BMD across adulthood. The most consistent evidence supports beneficial effects at the lumbar spine and femoral neck, whereas total hip evidence remains uncertain and low powered. NMA rankings suggest possible site-specific candidates, including AT+RT/TCE for lumbar spine, RT and possibly AE for femoral neck, AT/TCE-related modalities for Ward's triangle, and IE/RT for total body BMD, but these rankings should be interpreted cautiously because many CrIs overlapped and NMA certainty was often limited. Signals favoring supervised programs and interventions of at least six months should be regarded as exploratory subgroup findings rather than universal prescriptions. Future trials should directly compare active modalities, report bone-specific loading parameters, and provide standardized dose information to support clinically actionable exercise prescriptions.

CRediT authorship contribution statement

Huan Feng: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **ZhengWei Xie:** Project administration, Methodology, Funding acquisition, Formal analysis, Data curation. **Yubo Wang:** Validation, Supervision, Methodology, Data curation. **Yunan Zhang:** Supervision, Software, Formal analysis. **Haojiang Zuo:** Writing – review & editing, Validation, Software, Formal analysis, Data curation. **Hui Yang:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Clinical trial number

Not applicable.

Ethics approval

Not applicable.

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Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

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Not applicable.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bone.2026.118044.

Data availability

The datasets generated and analysed during the current study, together with the analysis code and reviewer-requested audit tables, will be deposited in an open repository upon acceptance; they are available

from the corresponding author on reasonable request during peer review.

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