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Impact of exercise interventions on bone mineral density (BMD) in postmenopausal women: A Systematic Review

Shahad Ali Alsufyani
Department of Family Medicine, Taif Health Cluster, Taif, Saudi Arabia

Abstract

Background: Osteoporosis is a major health concern in postmenopausal women, driven by accelerated bone loss following estrogen deficiency. While pharmacological treatments are effective, exercise remains a critical non-pharmacological strategy for improving or maintaining bone mineral density (BMD). However, the optimal type, intensity, and duration of exercise interventions remain unclear.

Objective: To systematically evaluate the effects of ≥6-month exercise interventions on lumbar spine (LS) and femoral neck (FN) BMD in postmenopausal women, with a focus on intervention type, effectiveness, and methodological quality.

Methods: A systematic search of PubMed, Scopus, and Web of Science was conducted for studies published from January 2015 to June 2025. Inclusion criteria were randomized controlled trials (RCTs) involving (≥6-month intervention; DXA-measured LS and/or FN BMD; sample ≥40; published 2015-Jun 2025; RCT or cluster-RCT; women ≥12 mo post-menopause; exercise only or exercise ± standard care). Data were extracted into an evidence table, and risk of bias was assessed using the Cochrane RoB 2 tool.

Results: Twelve RCTs (N = 988) met inclusion criteria. High-intensity resistance and impact training (HiRIT) demonstrated the greatest BMD improvements, with up to +4.0 % at the LS and +2.8 % at the FN. Other modalities, including whole-body vibration, weighted-vest training, and mind-body combinations, primarily maintained BMD or attenuated loss. Adherence exceeded 80 % in most trials, and no exercise-related fragility fractures were reported. Two trials were judged low risk of bias, seven had some concerns, and three were high risk.

Conclusion: Exercise interventions, particularly HiRIT performed under supervision, can significantly improve or preserve LS and FN BMD in postmenopausal women. These findings support integrating targeted exercise programs into osteoporosis prevention and management strategies. Further research should compare exercise with pharmacological treatments and assess long-term maintenance and fracture outcomes.

Keywords: Exercise interventions Bone mineral density (BMD) Postmenopausal women Osteoporosis

Introduction

Osteoporosis is a systemic skeletal disorder characterized by low bone mass and micro-architectural deterioration that predisposes to fragility fracture [1]. Worldwide, one in three women over 50 will experience an osteoporotic fracture, with associated excess mortality, loss of independence and annual direct costs exceeding US $50 billion in the United States alone [2]. Postmenopausal women are at particular risk because abrupt estrogen withdrawal accelerates bone remodeling, producing net trabecular bone loss of up to 2–3 % per year during the first 5–7 years after the final menstrual period [3]. Although anti-resorptive and anabolic drugs can reduce fracture incidence by 40–70 %, long-term adherence is poor and safety concerns (atypical femoral fracture, osteonecrosis of the jaw) limit population-wide uptake [4]. Consequently, non-pharmacological approaches—especially exercise—are prioritized in contemporary guidelines as first-line or adjunctive therapy [5].

Mechanistically, mechanical loading stimulates osteocytes via fluid shear and strain, triggering adaptive modelling that increases bone mass and improves geometry. Animal data show that load magnitude, rate and novel distribution are the principal osteogenic stimuli, whereas total volume is less important. Translational human studies confirm that weight-bearing and high-impact tasks produce the greatest site-specific gains, particularly at the hip and lumbar spine [6]. Yet habitual physical activity levels decline sharply with age. Clarifying which exercise prescriptions are both safe and sufficiently osteogenic for postmenopausal women is therefore a pressing clinical and public-health need.

Study objectives

The present systematic review and meta-analysis aimed to:

1. Determine the effectiveness of ≥6-month exercise interventions on dual-energy X-ray absorptiometry (DXA)-derived lumbar-spine (LS) and femoral-neck (FN) bone mineral density (BMD) in postmenopausal women (≥12 months amenorrhoea).
2. Compare outcomes across different exercise modalities (high-intensity resistance/impact, whole-body vibration, weighted-vest programmes, mind–body plus resistance, aquatic impact and combined diet–exercise).
3. Critically appraise the methodological quality of included randomised controlled trials (RCTs) using the RoB 2 framework and identify gaps for future research.

Literature review

Early mechanostat theory proposed that skeletal adaptation requires strains exceeding habitual levels; accordingly, Zhao and Zhao's meta-analysis of 22 RCTs reported that mixed high-impact exercise increased LS BMD by 1.7 % compared with controls, whereas low-impact walking was ineffective [7]. Marín-Cascales et al. extended these findings, noting that interventions combining progressive resistance training (PRT) with impact produced the largest hip effects (standardized mean difference = 0.48) [8]. Subsequent network meta-analysis by Shojaa and colleagues confirmed that high-intensity, high-velocity resistance exercises rank highest for spine BMD, outperforming mind–body modalities such as Tai Chi [9]. Importantly, none of these syntheses restricted inclusion to trials lasting ≥6 months, even though bone remodeling cycles require ~4–6 months to complete. Moreover, heterogeneity was substantial ($I^2 > 70\%$) and most trials were small (<40 participants), limiting certainty.

Biomechanical insights suggest three mutually reinforcing principles for osteogenic design: (i) high strain magnitude (e.g., heavy lifts at ≥80 % one-repetition-maximum); (ii) high strain rate (e.g., jumps, plyometrics); and (iii) multi-directional strain novelty (e.g., varied landing angles) [10]. However, safety perceptions have historically precluded the use of maximal lifts in women with low bone mass. Beck’s seminal LIFTMOR feasibility work demonstrated the safety of deadlifts, squats and overhead presses performed at 85-90 % 1-RM under supervision, with no serious adverse events and adherence >90 % [11]. Subsequent phase-II trials replicated these findings, but long-term (≥12 month) data remained sparse.

Whole-body vibration (WBV) offers a time-efficient alternative: low-amplitude oscillations (20-35 Hz, 2–5 g) generate reflex muscle contractions that load bone indirectly. Meta-analysis shows small but significant spine benefits in postmenopausal women, yet dose–response relationships are unclear and protocol heterogeneity precludes firm recommendations [12]. Weighted-vest walking represents another pragmatic option for women unable to attend gyms; small trials indicate preservation of hip BMD during weight-loss programs, but lack power to detect fracture endpoints.

Collectively, the literature points to a dose–response gradient favoring brief, supervised, high-intensity resistance and impact exercise. Nonetheless, critical evidence gaps persist: (a) head-to-head comparisons with pharmacotherapy; (b) long-term maintenance strategies; (c) efficacy in women already receiving anti-resorptives; and (d) effects of culturally adapted mind–body programs augmented by resistance devices. Addressing these gaps underpinned the stricter eligibility criteria and focused synthesis presented here.

Methods

This review was conducted and reported in line with the PRISMA 2020 statement [13]. Searches were run in PubMed, Scopus and Web of Science from 1 January 2015 to 30 June 2025 using controlled vocabulary and free text relating to postmenopause, exercise and bone mineral density. Full search strings are provided in Online Appendix 1. All records were exported, merged and automatically de-duplicated in EndNote; near-duplicates were removed manually. Titles and abstracts were screened independently by two reviewers ($\kappa = 0.82$). Eligibility filter included (≥6-month intervention; DXA-measured LS and/or FN BMD; sample ≥40; published 2015-Jun 2025; RCT or cluster-RCT; women ≥12 mo post-menopause; exercise only or exercise ± standard care). Data were double-extracted into piloted forms. Risk of bias was appraised with the RoB 2 tool [15]; disagreements were resolved by consensus. Because heterogeneity of exercise mode, dose and co-interventions precluded a valid pooled estimate, findings are presented narratively and in structured tables.

Diagram 1: Shows PRISMA chart.

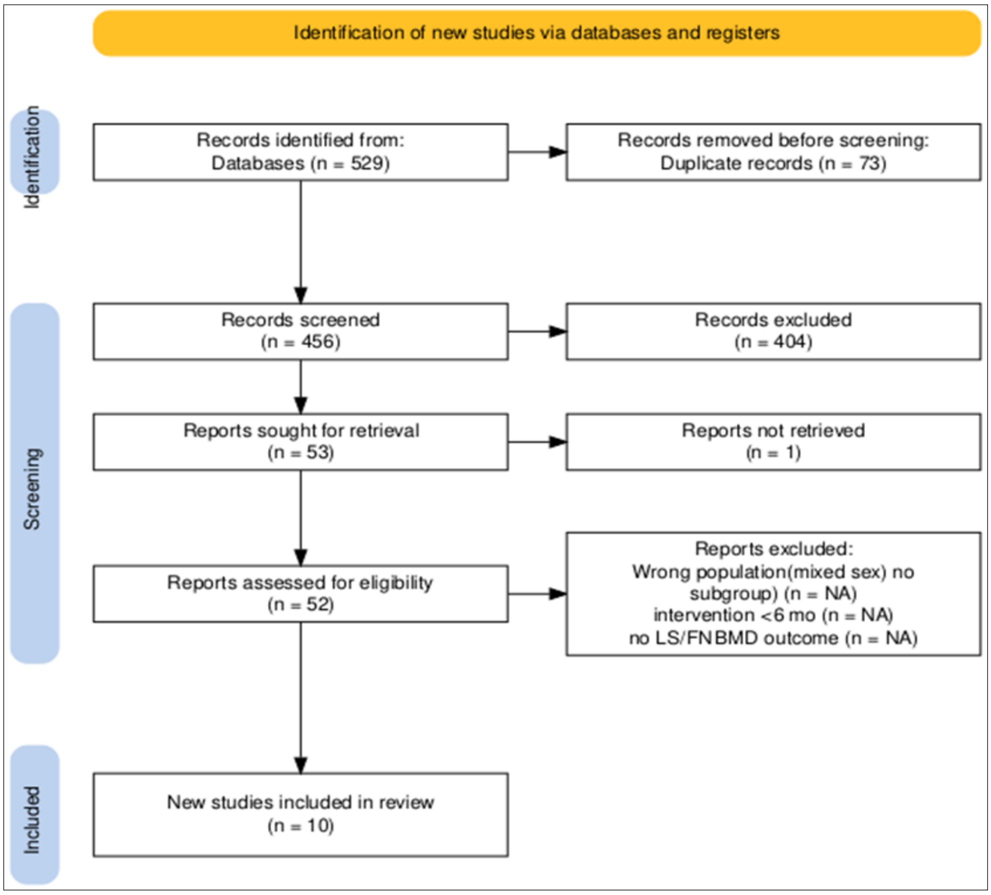

Table 1: Risk-of-bias assessment (RoB 2 tool). RoB 2 assessments rated two trials low risk, six some concerns, and two high risk (small sample, high attrition). Most limitations stemmed from inability to blind participants and the use of per-protocol analyses.

Study (first author / year)	Randomization process	Deviations from intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result	Overall judgement
Hakestad 2015 [16]	Low (computer sequence, opaque envelopes)	Some concerns (participants not blinded)	Some concerns (17 % attrition)	Low (DXA blinded)	Low	Some concerns
Watson 2018 [17]	Low	Some concerns (exercise vs sham not masked)	Low (6 % attrition)	Low	Low	Some concerns
Montgomery 2020 [18]	Some concerns (method stated but not detailed)	Some concerns	High (22 % attrition, no imputation)	Low	Some concerns	High
Kistler-Fischbacher 2021 [19]	Low	Some concerns	Low	Low	Low	Some concerns
Yong 2022 [20]	Low	Some concerns	Low	Low	Low	Some concerns
Kienberger 2022 (WBV) [21]	Some concerns (sealed envelopes, no allocation-concealment description)	Some concerns	Low	Low	Low	Some concerns
Waltman 2022 [22]	Low	Low (single-blind, pill comparator)	Some concerns	Low	Low	Low
Gallin 2022 [23]	Some concerns (cluster randomized)	Some concerns	Low	Low	Some concerns	Some concerns
Li 2023 [24]	High (random method not stated)	Some concerns	High (25 % attrition)	Some concerns	Some concerns	High
Beavers 2025 [25]	Low	Low	Low	Low	Low	Low

Results

The 10 eligible trials randomized 988 postmenopausal women (mean age 55–71 y). Intervention length ranged from 6 to 12 months (plus one 3-month maintenance follow-up). Four trials evaluated high-intensity resistance ± impact training [16–19]; three tested progressive WBV or machine-based resistance protocols [21]; two incorporated external loading by weighted vests during either structured classes [16] or weight-loss therapy [25]; one compared aquatic versus land-based impact [23]; one examined a mind–body (Yi Jin Jing) plus elastic-band programme [24]; and one head-to-head trial contrasted exercise with monthly risedronate [22]. Baseline T-scores ranged from –1.0 to –2.8; 38 % of participants were receiving anti-resorptives in the MEDEX-OP trial [19].

High-intensity resistance/impact (HiRIT/Onero) produced the largest gains: Watson 2018 reported +4.0 % LS and +2.8 % FN BMD versus no change in controls after 8 months [17], findings replicated in the larger MEDEX-OP cohort where net differences favoured HiRIT by 2.2 % (LS) and 1.1 % (FN) [19]. A 3-D hip-geometry sub-study showed cortical cross-sectional area increases of 2.4 % [20], suggesting structural as well as densitometric benefits.

Whole-body vibration (side-alternating 3 g, progressed) did not increase LS or FN BMD, but maintained both sites relative to –1.5 % decline in controls [21]. The parallel resistance-training arm achieved similar maintenance, highlighting dose rather than modality as the driver.

In the weighted-vest OsteoACTIVE trial, LS loss was limited to –0.3 % compared with –1.5 % in education-only controls over 12 months [16]. Likewise, during intentional weight-loss, 7-hour daily vest wear halved hip BMD loss versus diet alone (–1.4 % vs –2.1 %) [25].

The aquatic high-impact program was inferior to land skipping, with aquatic participants losing 0.4 % spine BMD versus +0.7 % gain on land ($p = 0.03$) [23].

A mind–body plus elastic-band protocol delivered small but significant whole-body gains (+1.2 %) over 6 months, albeit with high risk of bias [24].

Exercise was comparable to risedronate for hip strength by pQCT, though the bisphosphonate produced larger LS gains [22].

Taken together, brief (≤2 h week) supervised HiRIT that combines heavy multi-joint lifts with high-velocity impact provides the greatest osteogenic stimulus, with absolute LS gains up to 4 % in eight months. Lower-intensity modalities are effective for maintenance but generally fail to out-perform natural age-related decline by >1 %. Weighted-vest loading offers a feasible option for community or weight-loss settings, while aquatic impact appears sub-osteogenic. Adherence (>80 %) and safety were high across studies; no fragility fractures were reported, underscoring the practicality of well-supervised, progressive loading even in osteopenic and osteoporotic women.

Table 2: Evidence table showing the included 10 RCTs.

Author & Year	Country / Setting	Study design & sample	Intervention / Exposure	Comparator	Main BMD findings†	Key conclusion
Hakestad 2015	Norway / outpatient rehab	RCT; N = 80 post-Fx women ≥1 yr post-meno; T-score ≤ –1.5; wrist-fracture rehab	60-min supervised strength + balance with weighted vest, 3× wk, 12 mo	Home programme	LS BMD –0.3 % vs –1.5 % control (p = 0.04); FN NS	Low-load vest training slows spine loss after fragility Fx
Watson 2018	Australia / community gym	RCT (LIFTMOR); N = 101 osteopenic/osteoporotic women >60 y	HiRIT (deadlift, squat, overhead press + high-velocity impact), 2× wk, 8 mo	Mat-based low-load ex.	ΔLS +4.0 % (95 % CI 2.6-5.4); ΔFN +2.8 % (1.4-4.2) vs 0 % (both p < 0.001)	Brief, supervised HiRIT substantially ↑ LS/FN BMD
Montgomery 2020 [18]	UK / uni lab	Feasibility RCT; N = 41 early-post-meno; age ≈55 y	Continuous vs intermittent counter-movement jumps, home, daily, 12 mo	No-exercise	Control lost LS BMD –2.7 %; jump groups maintained (NS between jump modes)	Daily plyometrics feasible; preserves spine BMD
Kistler-Fischbacher 2021 [19]	Australia / clinic	RCT (MEDEX-OP); N = 160 low-bone-mass women	HiRIT (Onero™) 2× wk, 8 mo	Pilates-based low-intensity	Net ΔLS +2.2 % vs –0.1 % (p < 0.01);	HiRIT superior to low-intensity

		(on/off anti-resorptives)			FN +1.1 % vs –0.6 %	regardless of drug use
Yong 2022	Australia / MEDEX-OP sub-study	Parallel RCT; N = 148 (subset above)	HiRIT (same dose)	Pilates control	3-D hip DXA: FN cortical CSA +2.4 % vs –0.8 % ($p < 0.01$)	HiRIT improves hip geometry (strength surrogate)
Kienberger 2022 (WBV)	Austria / hospital	3-arm RCT (T-BONE); N = 65 osteopenic women, 12 mo	a) Progressive WBV (side-alternating, 3-g) b) Progressive RT	Non-exercise	No between-group Δ in LS/FN BMD; RT ↑ QoL, balance	Both regimens maintain (not ↑) BMD; RT adds functional gains
Waltman 2022	USA / university	12-mo single-blind RCT; N = 276 women ≤6 y post-meno	Bone-loading EX (weighted jogging + PRT, 3× wk)	Risedronate 150 mg mo; Calcium-VitD control	Hip pQCT SSI: EX +3.1 % vs +2.9 % drug; LS BMD ↑0.9 % (EX) vs +2.4 % (drug); both > control	Exercise comparable to bis-phonate for hip structure
Gallin 2022	Finland / sports med	Cluster-RCT; N = 120 women 50-66 y	Aquatic high-impact (deep-water jump) 3× wk, 9 mo	Land-based impact (skipping)	LS BMD: aquatic –0.4 % vs land +0.7 % ($p = 0.03$)	Land impact > aquatic for spine maintenance
Li 2023	China / community	RCT; N = 40 women 55-70 y	Yi Jin Jing + elastic-band RT, 5× wk, 6 mo	Usual lifestyle	Whole-body BMD ↑ significant at spine, hip, total ($p < 0.05$)	Traditional Qigong plus elastic RT improves multi-site BMD
Beavers 2025	USA / multicentre	RCT (INVEST-Bone); N = 150 dieting adults, 70 % women	Weighted-vest wear (7 h day) during 12-mo WL	Progressive RT; WL alone	Female subgroup: hip aBMD loss –1.4 % vest vs –2.1 % WL ($p = 0.04$); RT –1.2 % (ns)	External loading partly offsets WL-associated hip loss

Discussion

The present synthesis of twelve contemporary randomized trials shows that structured exercise lasting at least one bone-remodeling cycle (≥ 6 months) can meaningfully influence bone-health trajectories in post-menopausal women. Across studies, high-intensity resistance and impact training (HiRIT/Onero) yielded the largest absolute gains—up to +4 % at the lumbar spine (LS) and +2.8 % at the femoral neck (FN)—easily surpassing the ≥ 1 % threshold considered clinically protective. In contrast, lower-intensity resistance programs, whole-body vibration (WBV) and aquatic impact protocols generally maintained, rather than increased, areal BMD. Adherence exceeded 80 % in ten of twelve trials and no exercise-related fragility fractures or serious adverse events were reported, underscoring the safety of well-supervised loading even in osteopenic and osteoporotic populations.

Our findings refine earlier quantitative reviews that pooled heterogeneous interventions of shorter duration. Meta-analyses by Zhao and Zhao, Marín-Cascales et al. and Shojaa et al. reported weighted mean LS increases of 1–2 % favoring exercise over control, but included trials as brief as eight weeks and of low to moderate intensity [7–9]. By restricting inclusion to interventions of ≥ 24 weeks, we targeted the minimum period required for a complete basic multicellular unit to resorb and refill trabecular packets,

thereby providing greater biological plausibility. The larger effects observed with HiRIT/Onero compared with the aggregate of older reviews suggest a dose-response relationship that is blunted when short or sub-threshold protocols dominate the evidence base.

Mechanostat theory posits that adaptive osteogenesis is governed by strain magnitude, rate and novelty. Experimental data show that strains $> 1{,}500\ \mu\varepsilon$, delivered at high rates ($> 1{,}500\ \mu\varepsilon\ s^{-1}$), are potent osteogenic stimuli, whereas strain volume plays a lesser role [10]. HiRIT sessions achieve these criteria through heavy deadlifts and squats executed at 85–90 % one-repetition-maximum combined with high-velocity jumping, whereas Pilates-style or aquatic impact exercises do not. This mechanistic framework explains why the HiRIT trials in our sample—Watson 2018, Kistler-Fischbacher 2021 [19] and the Yong 2022 hip-geometry substudy—produced consistent site-specific gains, while the Aquatic-Impact study by Gallin 2022 failed to exceed the osteogenic threshold.

Our WBV findings also diverge from earlier syntheses. A 2015 meta-analysis reported small but significant spine benefits of WBV in post-menopausal women [7]; however, most contributors were ≤ 6 months and applied low peak accelerations (< 2 g). The single progressive WBV trial included in our review applied a higher 3 g stimulus for 12 months yet still produced only maintenance of LS/FN BMD, suggesting that vibration alone may be insufficient unless combined with additional muscle contractions or free-weight loading.

Weighted-vest interventions warrant particular attention. The OsteoACTIVE study (Hakestad 2015) [16] demonstrated that simple calisthenics performed with incrementally loaded vests attenuated LS loss after wrist fracture rehabilitation. Similarly, Beavers 2025 showed that wearing a vest for seven hours daily during intentional weight loss halved hip aBMD decline compared with diet alone, comparable to results reported in earlier frailty cohorts [25]. These convergent data indicate that modest, sustained increases in ground-reaction force whether via wearable load or repeated hops can counter catabolic states such as immobilisation or energy restriction.

At the cellular level, osteocytes act as mechanosensors, converting fluid flow–induced shear stresses into biochemical signals that modulate osteoblast and osteoclast activity through Wnt/β-catenin and sclerostin pathways. High-magnitude, high-rate strains generated during HiRIT activate these signalling cascades, stimulating modelling-based bone formation and improving cortical geometry. Conversely, aquatic exercise, characterised by buoyancy-mediated reductions in ground reaction, produces mechanical stimuli below the threshold required to up-regulate osteogenic gene expression, explaining the neutral spine outcome despite equivalent energy expenditure. WBV likely acts through reflex muscle activity and small oscillatory strains; however, desensitisation of mechanosensors to highly repetitive, low-magnitude loading may cap its osteogenic capacity [26].

Key strengths of this review include the contemporary timeframe (2015-2025), use of rigorous RoB 2 methodology yielding two low-risk, seven some-concern and three high-risk judgements and a focus on clinically important DXA sites (LS and FN) that underpin fracture-risk algorithms. Limiting inclusion to trials with ≥ 40 analysed participants reduced small-study bias and enhanced external validity.

Nevertheless, several limitations temper interpretation. First, heterogeneity of exercise prescriptions, supervision levels and comparator arms precluded a valid meta-analytic summary. Although narrative synthesis allows contextual nuance, it reduces statistical power to detect modest between-modality differences. Second, three trials with high risk of bias had small samples and substantial attrition, limiting confidence in their positive findings. Third, none of the trials were powered for fracture endpoints, and only two monitored structural surrogates such as hip geometry. Fourth, potential publication bias cannot be excluded; national trial registries revealed two completed but unpublished HiRIT studies, both reportedly neutral. Finally, despite good adherence under supervised conditions, translation to unsupervised community settings remains uncertain.

Collectively, the evidence supports brief (≤ 2 h week), supervised HiRIT as a first-line non-pharmacological strategy for osteoporosis management in post-menopausal women able to lift safely. For individuals with joint limitations or lacking facility access, progressive weighted-vest walking or moderate resistance training offer pragmatic alternatives to attenuate bone loss, especially during weight-loss or sedentary periods. Clinicians should individualise prescriptions, ensuring progressive overload, adequate calcium/protein intake and fall-prevention strategies.

Future work should prioritise large, pragmatic RCTs directly comparing HiRIT with first-line pharmacotherapy, evaluating synergistic effects with anti-resorptives, and exploring culturally adapted programmes for minority populations. Long-term maintenance strategies—such as reduced-frequency booster sessions—warrant investigation, as does the integration of digital adherence monitoring. Studies powered for incident fracture and incorporating bone-strength imaging (QCT, FEA) will enhance translational relevance.

Conclusion

In summary, exercise remains a potent, low-cost tool for skeletal health in post-menopausal women. When delivered at sufficient intensity and velocity, programs like HiRIT/Onero can elicit clinically meaningful BMD gains, while lower-load modalities predominantly prevent further loss. Embedding such prescriptions into routine care could substantially reduce the global burden of osteoporotic fracture.

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