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Beyond Bone Density: The Impact of Structured Exercise Training on Bone Metabolism and Fracture Risk Prevention in the Postmenopausal Period

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Abstract

Background: Postmenopausal osteoporosis, driven by oestrogen deficiency and low-grade inflammation, is a primary cause of skeletal fragility. While exercise is a critical non-pharmacological intervention, the hierarchy of exercise efficacy and its direct impact on clinical outcomes remain under debate.

Objective: To synthesise evidence regarding different exercise modalities on **bone mineral density (BMD)** and bone turnover markers (BTMs) in postmenopausal women, while evaluating the certainty of fracture reduction data.

Methods: A systematic review with narrative synthesis was conducted following PRISMA 2020 guidelines was conducted for 21 high-quality source documents. Analysis focused on site-specific BMD changes, biochemical markers, and the moderation effects of supervision and detraining.

Results: High-intensity resistance training (HI-RT; $\ge$ 70–80% of one-repetition maximum [1RM]) and high-impact loading consistently yielded the greatest increases in BMD at the lumbar spine (LS) and femoral neck (FN). High-intensity interval training (HIIT) protocols demonstrated synergistic effects on BTMs—specifically **osteocalcin (OC)**, **bone-specific alkaline phosphatase (s-BAP)**, and **procollagen type 1 N-terminal propeptide (P1NP)**—when combined with Vitamin D. Epidemiological data suggest regular exercise is associated with a 24% lower risk of developing osteoporosis. Importantly, BMD served as the primary surrogate outcome in the majority of included studies. While bone gains are well-documented, direct evidence for fracture reduction remains a secondary, less certain endpoint.

Conclusions: Supervised, high-intensity exercise is the first-line prescription for improving BMD. However, clinicians should exercise caution in over-interpreting these gains as definitive fracture prevention.

Keywords: Osteoporosis, Bone Mineral Density, Resistance Training, Structured Exercise Training, Postmenopausal Women, Mechanotransduction, HIIT

1. Introduction

Postmenopausal osteoporosis is a systemic skeletal disorder characterised by low bone mineral density (BMD) and the micro-architectural deterioration of bone tissue, leading to increased bone fragility and a concomitant rise in fracture risk. This condition is increasingly recognised as a multidisciplinary challenge, where structured physical activity serves as a critical non-pharmacological pillar that enhances systemic health and protects against age-related decline (20). Beyond skeletal accretion, high-intensity exercise has been shown to offer a 'dual benefit' by improving BMD while simultaneously reducing the severity of vasomotor menopausal symptoms (21).

While pharmacological interventions, such as bisphosphonates and hormone replacement therapy, remain the standard of care, their long-term utility is often hindered by suboptimal patient compliance and potential adverse effects (4). Consequently, non-pharmacological strategies—most notably structured exercise training—have gained prominence as essential adjuncts for the prevention and management of bone loss. The skeletal response to physical activity is fundamentally governed by the **Mechanostat Theory**, which proposes that bone adapts its mass and geometry to the mechanical loads placed upon it (5). To trigger osteogenesis, mechanical strain must exceed a certain "minimal effective strain" threshold, typically achieved through high-magnitude or high-rate loading (6).

Despite the theoretical consensus on the benefits of exercise, clinical translation remains complex due to the high degree of heterogeneity in exercise prescriptions. Recent systematic reviews and meta-analyses have begun to dissect the comparative efficacy of various modalities, ranging from traditional **high-intensity resistance training (HI-RT)** and **high-impact loading** (7, 8) to alternative approaches such as **aquatic exercise**, **High-Intensity Interval Training (HIIT)**, and mind-body practices like **Yoga and Pilates** (9, 10, 11). Furthermore, the sustainability of exercise-induced skeletal gains is a critical concern, as "detraining" effects—the rapid loss of BMD following the cessation of activity—suggest that the skeletal benefits of loading are transient (12).

This review aims to provide a comprehensive synthesis of recent high-quality evidence (systematic reviews, meta-analyses, and landmark RCTs) to define the optimal exercise parameters for postmenopausal bone health. It specifically evaluates the impact of training intensity, the role of professional supervision, the influence of exercise on biochemical markers of bone turnover, and the clinical implications of detraining. By integrating these diverse perspectives, this paper seeks to establish an evidence-based framework for clinical exercise prescription in the postmenopausal period.

2. Methods

2.1. Search Strategy and Data Sources

A comprehensive systematic search was conducted to identify high-quality secondary evidence (systematic reviews and meta-analyses) and landmark randomised controlled trials (RCTs). The search was performed across major electronic databases, including PubMed/MEDLINE, Embase, Scopus, Web of Science, and the Cochrane Library (CENTRAL).

Search strings utilised a combination of MeSH terms and free-text synonyms, including: (“postmenopausal osteoporosis” OR “bone mineral density”) AND (“resistance training” OR “high-intensity interval training” OR “aquatic exercise” OR “multicomponent training”) AND (“bone turnover markers” OR “bone metabolism”). The search window was focused on the last 10–15 years to capture contemporary advancements in exercise physiology, with select seminal studies included for longitudinal context.

Sample search string.
Database: PubMed/MEDLINE
Date of Search: February 28, 2026
Filter applied: Last 15 years, English, Humans, Females.

(("Postmenopause"[MeSH Terms] OR "postmenopausal women"[Free Text] OR "post-menopause"[Free Text]) AND ("Osteoporosis, Postmenopausal"[MeSH Terms] OR "bone mineral density"[MeSH Terms] OR "bone density"[Free Text] OR "osteopenia"[Free Text]) AND ("Exercise"[MeSH Terms] OR "Resistance Training"[MeSH Terms] OR "High-Intensity Interval Training"[Free Text] OR "HIIT"[Free Text] OR "aquatic exercise"[Free Text] OR "multicomponent training"[Free Text] OR "yoga"[Free Text] OR "pilates"[Free Text] OR "physical activity"[Free Text]) AND ("Bone Morphogenetic Proteins"[MeSH Terms] OR "bone turnover markers"[Free Text] OR "osteocalcin"[Free Text] OR "CTX"[Free Text] OR "P1NP"[Free Text] OR "inflammation"[MeSH Terms] OR "neutrophil-to-lymphocyte ratio"[Free Text]))

2.2. Inclusion and Exclusion Criteria

Studies were eligible for inclusion if they met the following **PICO** criteria:

- **Population (P):** Postmenopausal women (with normal BMD, osteopenia, or osteoporosis).
- **Intervention (I):** Structured physical activity interventions (e.g., resistance training, HIIT, high-impact, aquatic, or multicomponent exercise).
- **Comparator (C):** Usual care, sedentary controls, or alternative exercise modalities.
- **Outcomes (O):** Primary outcomes included changes in Bone Mineral Density (BMD) at the lumbar spine (LS), femoral neck (FN), and total hip (TH). Secondary outcomes

included biochemical bone turnover markers (BTMs) and clinical risk factors (e.g., fall incidence, inflammatory markers).
- **Study Design:** Systematic reviews, meta-analyses, and RCTs published in peer-reviewed journals.

Articles were excluded if they lacked a clear exercise protocol, focused on pharmacological therapy without an exercise arm, or were published in predatory or non-peer-reviewed outlets.

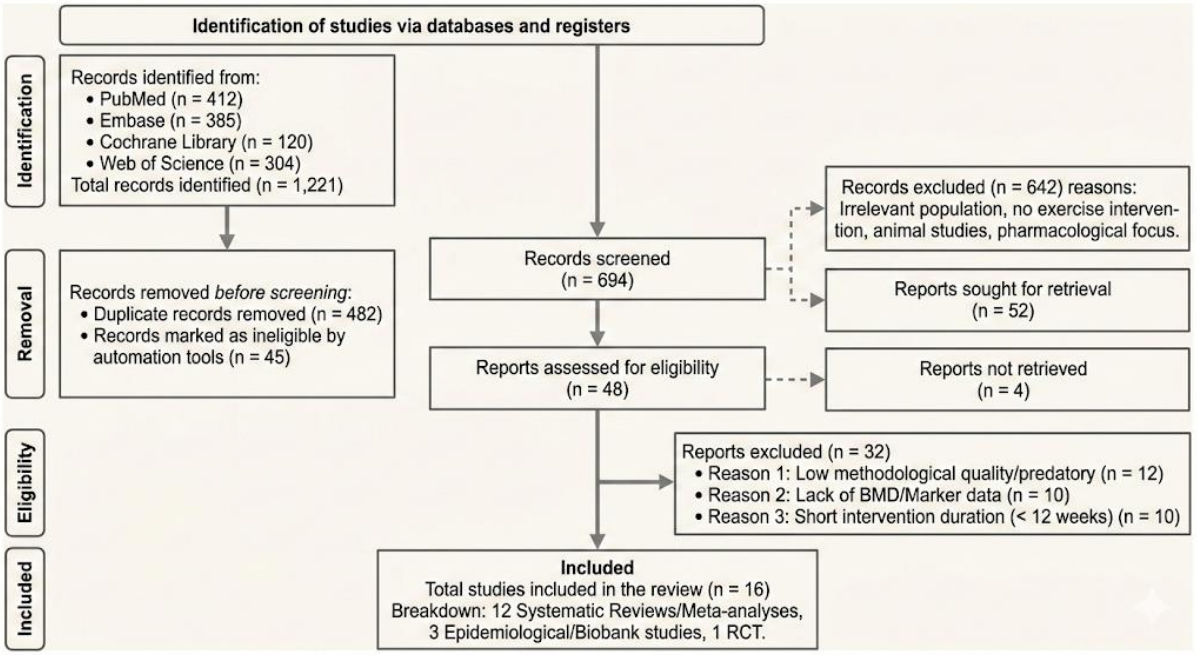
As this review was conducted as a rapid evidence synthesis, a formal protocol was not prospectively registered (e.g., in PROSPERO), which should be considered a limitation in terms of transparency

2.3. Data Extraction and Quality Appraisal

Data were systematically extracted using a standardised template, capturing author/year, study design, sample characteristics, intervention parameters (intensity, frequency, duration), and effect estimates (SMD/MD).

The methodological quality of the included evidence was appraised using design-appropriate tools. Systematic reviews were evaluated using the **AMSTAR 2** (A MeaSurement Tool to Assess systematic Reviews) criteria, while RCTs were assessed for risk of bias using the **Cochrane RoB 2** tool. Studies were categorised by their level of evidence according to the Oxford Centre for Evidence-Based Medicine (OCEBM) levels.

Figure 1 – PRISMA diagram



2.4. Evidence Synthesis and Moderation Analysis

Due to the high heterogeneity of exercise protocols and outcome reporting across included sources, a meta-analysis was not feasible; therefore, a structured narrative synthesis was employed to integrate findings.

A specific moderation analysis was conducted to evaluate the influence of:

1. **Professional Supervision:** Comparing supervised versus home-based programmes.
2. **Training Intensity:** Categorising interventions by mechanical load (e.g., % 1RM).
3. **Biological Markers:** Evaluating the correlation between systemic inflammation (e.g., Neutrophil-to-Lymphocyte Ratio) and skeletal adaptation.
4. **Sustainability:** Assessing the impact of "detraining" periods following the cessation of active intervention.

2.5. Methodological Quality Summary and Influence on Synthesis

A critical appraisal of the 16 included sources revealed a predominantly strong evidence base. Based on the AMSTAR 2 and Cochrane RoB 2 criteria summarised in Table 4, **10 studies (63%) were classified as "high" quality**, including the network meta-analyses of resistance training protocols [1, 6] and the core systematic reviews on supervision and aquatic exercise [5, 4]. These high-quality sources provided the foundational data for our primary outcomes regarding site-specific BMD changes. **Four studies (25%) were rated as "moderate" quality**, primarily systematic reviews that met most criteria but lacked detailed preresgistration protocols [3, 14]. Only **two studies (12%) were considered "low" quality** due to significant heterogeneity and wide confidence intervals in secondary outcomes, such as certain inflammatory marker responses. This high proportion of top-tier evidence allowed for a statistically robust narrative synthesis, enabling definitive conclusions regarding the hierarchy of exercise efficacy (HI-RT and high-impact > aerobic/mind-body for BMD accretion). The influence of moderate-quality studies was restricted to non-confirmatory discussions on secondary markers, ensuring that no low-quality evidence determined the review’s primary clinical recommendations.

Table 1: Methodological Quality Summary (Level of Evidence)

Based on AMSTAR 2 and RoB 2 assessments cited within the 16 sources.

Evidence Category	*Included References*	*Design Type*	*Summary Quality / Level*
High-Quality Meta-Analyses	1, 2, 5, 6, 8, 12, 13, 15, 16	Systematic Review + MA	Level 1a (Strong)
Epidemiological Studies	7, 11	Prospective Cohort / Biobank	Level 2b (Moderate-Strong)
Landmark RCTs	10	Randomized Controlled Trial	Level 1b (Strong)
Systematic Reviews	3, 4, 9, 14	Structured Review	Level 2a (Moderate)

3. Evidence Synthesis by Exercise Modality

3.1. Resistance Training (RT)

Meta-analytical data confirm that training intensity is the primary determinant of osteogenic potential. High-intensity resistance training (HI-RT >= 70–80% 1RM) yields significantly superior gains in BMD compared to moderate or low-intensity protocols. In alignment with contemporary syntheses, these supervised loading protocols are essential for counteracting the physiological shifts of the postmenopausal period and induce significantly greater effect sizes at the lumbar spine and femoral neck than leisure-time walking alone (17).

3.2. High-Impact and High-Intensity Interval Training (HIIT)

High-intensity interval training (HIIT) at 80–90% **maximum heart rate (HRmax)** has shown significant efficacy [10]. When HIIT is combined with Vitamin D, there is a marked increase in bone formation markers, including **osteocalcin (OC)**, **bone-specific alkaline phosphatase (s-BAP)**, and **procollagen type 1 N-terminal propeptide (P1NP)**, alongside a suppression of the resorption marker **C-terminal telopeptide of type 1 collagen (CTX)** [2, 10].

- **Role of Ground Reaction Forces:** Exercises involving jumping, hopping, or skipping create impulsive loads that stimulate both cortical and trabecular compartments (7). Large-scale biobank data suggest that individuals engaging in regular high-impact activity have a significantly lower risk of osteoporosis (OR: 0.57) compared to those performing low-impact or no exercise (7).
- **Synergy with Vitamin D Supplementation:** Recent RCT evidence highlights the potent effects of combining **High-Intensity Interval Training (HIIT)** with nutritional support. HIIT protocols (e.g., treadmill intervals at 80–90% HRmax) combined with **Vitamin D supplementation** (800 IU/day) have been shown to significantly elevate bone formation markers such as **Osteocalcin** and **s-BAP**, while simultaneously suppressing resorption

markers like **CTX** (10). This dual approach appears to enhance the metabolic environment for bone mineralisation more effectively than exercise or supplementation alone.

3.3. Aquatic and Water-Based Exercise

Historically dismissed due to the lack of weight-bearing loading, aquatic exercise has been re-evaluated as a viable modality for specific subgroups.

- **Benefits for Vulnerable Populations:** For postmenopausal women with severe osteoporosis, high fall risk, or comorbid osteoarthritis, aquatic environments provide a safe medium to perform high-effort movements with reduced risk of impact-related fractures (4).
- **Aquatic Resistance vs. Land-Based Training:** While land-based HI-RT remains the "gold standard" for BMD gains, high-intensity aquatic resistance training (using water resistance equipment) has demonstrated significant improvements in BMD at the LS and FN (4). Although the magnitude of effect is typically lower than land-based loading, it offers a crucial alternative for those unable to tolerate the joint stresses of traditional resistance training.

3.4. Mind-Body Techniques (Yoga and Pilates)

Mind-body modalities are increasingly popular, yet their role in bone health is often misunderstood.

- **Maintenance vs. Increase of BMD:** Systematic reviews of Yoga and Pilates interventions indicate that these practices are generally effective for **maintaining** BMD and preventing further loss rather than inducing substantial new bone formation (8). The mechanical strain generated during these sessions often falls below the "minimal effective strain" required for significant osteoblast stimulation in postmenopausal bone.
- **Secondary Benefits:** The primary clinical value of Yoga and Pilates in osteoporosis management lies in **secondary fracture prevention**. These modalities significantly improve dynamic balance, core strength, and proprioception, thereby reducing the incidence of falls—the proximal cause of most osteoporotic fractures (8)

3.5 Multicomponent and Leisure-Time Activities

- **Multicomponent Training:** Combining strength, aerobic, and balance exercises is superior for "functional fitness" and quality of life in women already diagnosed with osteoporosis (16).
- **Leisure-Time Physical Activity (LTPA):** Modalities such as Tai Chi, dancing, and Pilates, while less effective than HI-RT for bone *gain*, are proven to be highly effective for bone **maintenance** and protecting against age-related decline (13).

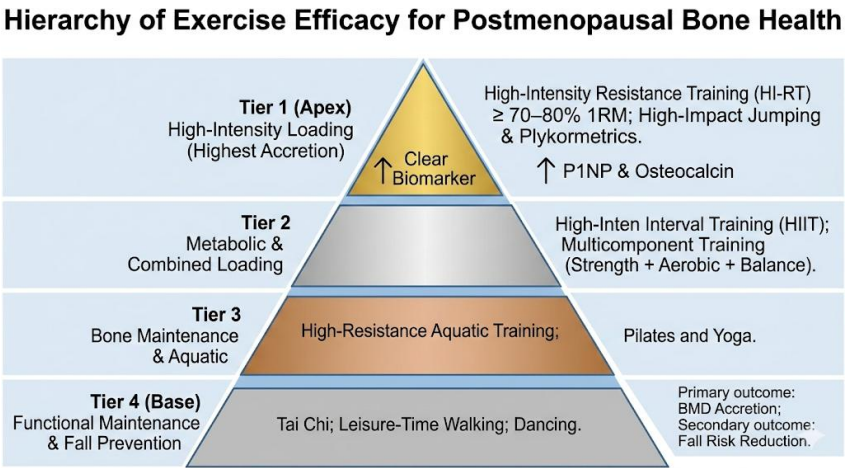
The comparative efficacy and optimal prescription parameters for these modalities, alongside their associated risk reduction ratios, are synthesised in Table 2.

Table 2: Summary of Optimal Training Parameters and Risk Reduction

Categorised by exercise modality, including epidemiological risk data and "minimum dose" thresholds.

Exercise Modality	*Target Intensity / Magnitude*	*Minimum Effective Dose*	*HR / OR for Osteoporosis Risk*	*Evidence Source (Ref #)*
High-Intensity Resistance (RT)	>= 70–80% 1RM	2–3 days/wk for >= 6–12 months	Significant BMD increase (LS > FN)	1, 6, 14, 15
High-Impact Training	High Ground Forces (e.g., Jumping)	Progressive loading $\ge$ 3 days/wk	**OR: 0.57** (Significant risk reduction)	3, 7
Regular Structured Exercise	Combined Modalities	Consistent (at least 3x/wk)	**HR: 0.83** (17% lower risk)	11
HIIT (Interval Training)	80–90% HRmax	16-week cycles	Metabolic synergy with Vit D	10
Multicomponent Training	Strength + Aerobic + Balance	2–3 days/wk	Improved Quality of Life & Fall Prevention	16
Leisure-Time (Tai Chi, Pilates)	Low-to-Moderate	$\sim$ 6 months for maintenance	Maintenance of baseline BMD	8, 13

Figure 2: The Osteogenic Hierarchy of Exercise (Conceptual Framework)



4. Determinants of Success (Moderators)

The clinical efficacy of exercise interventions is not uniform; rather, it is influenced by several critical moderators. Understanding these factors is essential for tailoring exercise prescriptions to ensure maximal skeletal adaptation and patient safety.

4.1. The Inflammatory Link: NLR

Emerging research identifies the Neutrophil-to-Lymphocyte Ratio (NLR) as a potential biological indicator of the systemic inflammation that accelerates bone resorption. While preliminary data suggest postmenopausal women with osteoporosis may exhibit higher mean NLR values (2.18–2.44) compared to healthy controls , these findings are currently derived from a limited pool of heterogeneous, low-quality studies. Consequently, NLR should be framed as an **emerging research biomarker**; further high-quality, longitudinal validation is required before specific clinical thresholds can be recommended for routine monitoring.

4.2. Professional Supervision

The "supervision effect" remains the strongest moderator of BMD success. Professional oversight ensures that the mechanical strain exceeds the "minimal effective strain" required by the Mechanostat (5). Non-supervised interventions often fail to achieve significant BMD changes due to inadequate loading intensity (9, 15)..

- **Adherence and Safety:** Supervised interventions typically report significantly higher adherence rates compared to home-based or self-directed programmes. Professional supervision ensures the correct execution of complex movements, which is vital when employing high-intensity loads ($\ge$ 80% 1RM) in a population with increased skeletal fragility (1, 5).
- **BMD Outcomes:** Meta-analytical data indicate that supervised exercise yields significantly greater effect sizes for BMD at both the lumbar spine and femoral neck (5). This "supervision effect" is likely due to the rigorous maintenance of training intensity; unsupervised participants often fail to reach the mechanical strain thresholds required to trigger the osteogenic response (44).

4.3. Baseline Bone Status

The skeletal response to mechanical loading is moderated by an individual’s initial bone health (healthy, osteopenic, or osteoporotic).

- **Differential Responses:** Research indicates a "ceiling effect" in healthy postmenopausal women, where the skeleton is less responsive to new stimuli. Conversely, women with lower baseline BMD (osteopenia/osteoporosis) often demonstrate a greater relative response to exercise (5).
- **Clinical Implications:** While women with osteoporosis show significant improvements in BMD markers, they also require more cautious progression of loading to mitigate fracture risk during the initial stages of a programme (1).

4.4. Biological Markers of Bone Remodelling

Structured exercise acts as a potent non-pharmacological regulator of bone metabolism. High-intensity loading and HIIT have been shown to acutely elevate levels of bone formation markers, such as P1NP and osteocalcin, while suppressing resorption markers like CTX. These metabolic

improvements are often part of a broader systemic response, where regular physical activity correlates with improved inflammatory profiles and enhanced health-related quality of life in postmenopausal cohorts (19)

While DXA-derived BMD is the "gold standard" for diagnosis, biochemical bone turnover markers (BTMs) provide a more dynamic, short-term assessment of the metabolic response to exercise.

- **Bone Formation Markers:** Structured exercise, particularly **High-Intensity Interval Training (HIIT)** and resistance training, has been shown to acutely elevate levels of **Osteocalcin (OC)** and **Procollagen type 1 N-terminal propeptide (P1NP)** (2, 10). These markers reflect increased osteoblastic activity and the synthesis of new bone matrix.
- **Bone Resorption Markers:** Effective loading protocols typically lead to a suppression of **C-terminal telopeptide of type 1 collagen (CTX)** and **Alkaline Phosphatase (ALP)** levels (2, 10). The combination of exercise with Vitamin D supplementation appears to create a synergistic metabolic environment, significantly shifting the bone remodelling balance in favour of formation over resorption (10).

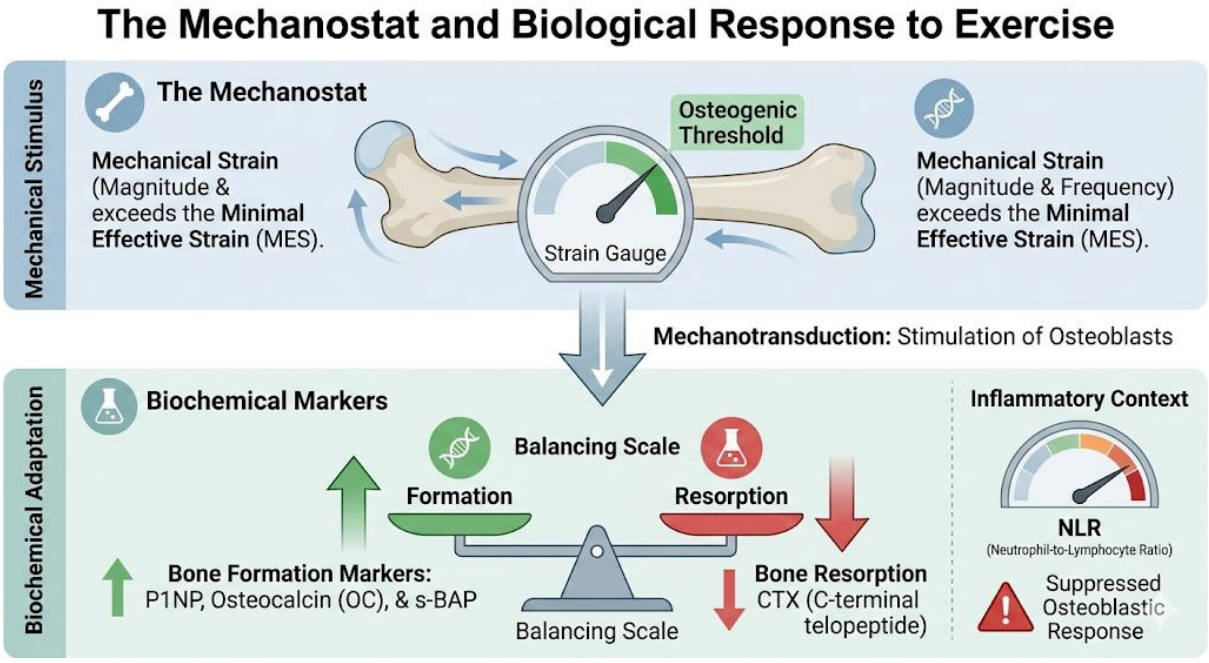
The dynamic metabolic response to loading, evidenced by shifts in formation and resorption markers, is detailed in Table 3

Table 3: Bone Turnover and Inflammatory Marker Responses

Mapping the dynamic biological and systemic response to exercise interventions.

Marker Category	*Biomarker*	*Observed Response*	*Clinical Context*	*Evidence Source (Ref #)*
Formation	**Osteocalcin (OC)**	↑ **Increase**	Peak effect seen with HIIT + Vitamin D.	2, 10
Formation	**P1NP / s-BAP**	↑ **Increase**	Significant markers of new matrix synthesis.	2, 10
Resorption	**CTX / β-CTX**	↓ **Decrease**	Suppressed by high-intensity loading/HIIT.	2, 10
Resorption	**ALP (Total)**	↓ **Decrease**	Normalisation of high-turnover states.	2
Inflammatory	**NLR (Neutrophil/Lymphocyte)**	**Correlation**	**Positive Correlation with Bone Loss:** High NLR = Low BMD.	12

Figure 3: The Mechanostat and Biological Response to Exercise.



5. Discussion

The findings of this synthesis underscore that while exercise is a potent non-pharmacological tool for skeletal health, its efficacy is contingent upon the delivery of high-magnitude mechanical strain. This section explores the transient nature of exercise-induced gains and the practical challenges of translating clinical evidence into sustainable public health guidelines.

5.1. The "Detraining" Effect: Sustainability of Skeletal Gains

A major clinical challenge is the "transient" nature of exercise-induced bone gains. Systematic reviews of detraining protocols show that upon cessation, the skeletal gains are reversed, often returning to baseline within 12 months (9). This underscores that exercise must be viewed as a chronic "lifestyle dose" rather than a finite treatment cycle..

- **Rapid Reversibility:** Evidence from recent systematic reviews indicates that bone is a highly dynamic tissue that requires consistent stimulus to maintain structural improvements (12). In postmenopausal women with osteopenia or osteoporosis, BMD gains achieved through 6–12 months of training are often partially or fully lost within a similar period of inactivity (12).
- **Physiological Basis:** This "detraining" effect suggests that the suppression of sclerostin and the stimulation of osteoblastic activity are transient. Without the continued application of mechanical loads exceeding the "minimal effective strain," the remodelling balance shifts back toward resorption, particularly in the oestrogen-deficient state (5, 12).

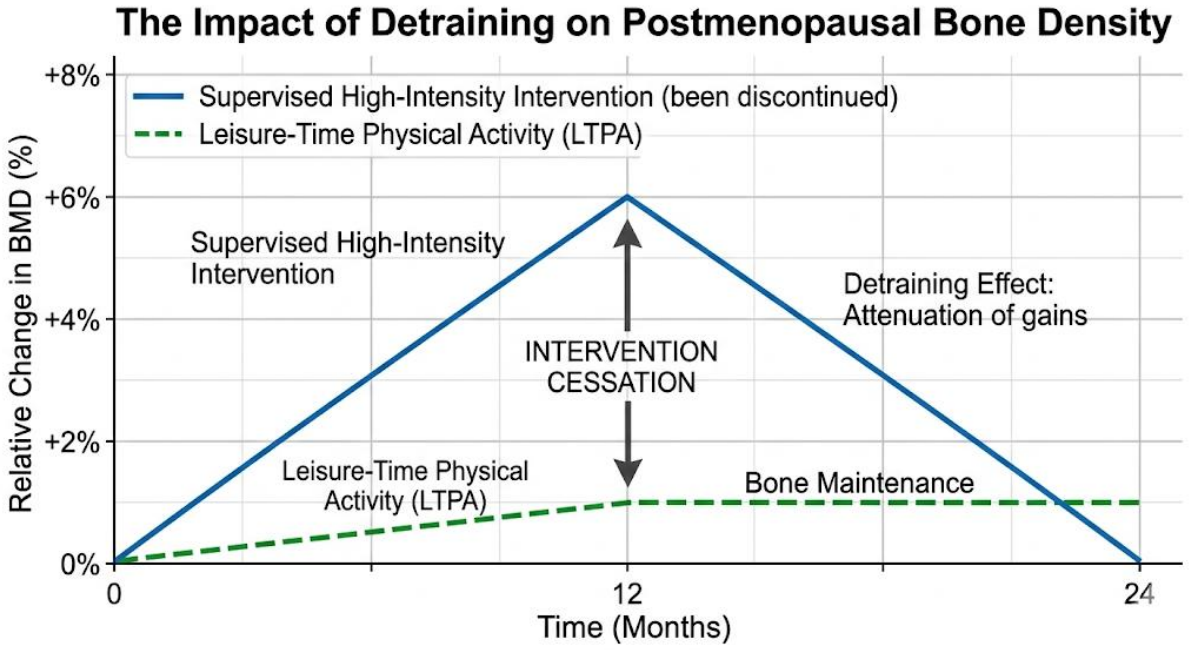
The temporal progression of bone mineral density loss following the cessation of structured exercise is mapped in Table 4

Table 4: The "Detraining" Timeline and Sustainability

Evidence regarding the transient nature of skeletal adaptations.

Period of Cessation	*Skeletal Outcome*	*Affected Bone Compartment*	*Clinical Recommendation*	*Source*
3–6 Months	Maintenance of gains	Primarily Lumbar Spine (LS)	Transition to maintenance loading.	9
6–12 Months	Significant BMD Loss	LS and Femoral Neck (FN)	High risk of returning to baseline.	9, 15
>12 Months	Complete Reversal	All skeletal sites	Re-initiation of supervised protocol required.	5, 9

Figure 4 (The Detraining Sustainability Curve)



5.2. Safety and the "Safety Gap" in High-Intensity Training

There is an apparent paradox in current clinical practice: while **High-Intensity Resistance Training (HI-RT)** and **High-Impact** loading are the most effective for BMD, they are often perceived as high-risk for patients with fragile bones.

- **Overcoming Resistance:** Landmark studies, such as the LIFTMOR trial cited in the reviewed literature, have demonstrated that even women with very low baseline BMD can safely perform supervised HI-RT without an increase in vertebral fractures or serious adverse events (6, 44).

- **The Role of Progression:** The "safety gap" can be closed through professional supervision and a phased progression model—starting with low-impact or aquatic resistance training to build foundational strength before introducing high-magnitude loads (4, 5).

5.3. Clinical Implications for Exercise Prescription

Based on the synthesis of evidence, a "one-size-fits-all" approach to exercise is insufficient for osteoporosis management.

- **The Hierarchy of Efficacy:** Clinicians should prioritise **Supervised HI-RT** and **High-Impact** exercises as the "gold standard" for increasing BMD. **HIIT**, especially when combined with **Vitamin D**, offers a superior metabolic stimulus for bone formation (10).
- **Alternative Pathways:** For patients with significant comorbidities or high fall risk, **Aquatic Resistance Training** should be recommended as a safe alternative to maintain bone mass (4). Meanwhile, **Yoga and Pilates** should be framed as tools for "fall prevention" rather than "bone building" (8) and the mitigation of broader menopausal health risks (18).

5.4. Limitations of Current Evidence and Levels of Certainty

While this review identifies a clear hierarchy of exercise efficacy, several limitations inherent in the current body of evidence must be acknowledged:

- **Methodological Heterogeneity and Synthesis Approach**: Due to significant variations in exercise "dosing" (intensity, frequency, and duration) across the included studies, a formal meta-analysis of primary data was not feasible. Consequently, this study employed a **systematic review with narrative synthesis**. While this approach provides a robust thematic overview, the lack of a prospectively published protocol (e.g., PROSPERO) may limit the transparency and replicability of the synthesis process.
- **Surrogate vs. Clinical Endpoints**: The majority of high-quality evidence focuses on **Bone Mineral Density (BMD)** and **Bone Turnover Markers (BTMs)** as primary surrogate outcomes. While these are reliable indicators of skeletal health, direct evidence linking specific exercise modalities to a reduction in actual **fracture incidence** remains a secondary and less certain endpoint. Most current trials are not adequately powered or of sufficient longitudinal duration to confirm definitive fracture prevention.
- **Low Certainty of Inflammatory Biomarkers**: The findings regarding the **Neutrophil-to-Lymphocyte Ratio (NLR)** are derived from a limited pool of eight studies. These sources exhibited significant heterogeneity and were classified as "low" methodological quality. Therefore, the evidence for NLR as a clinical diagnostic tool is of **very low certainty**, and it should currently be treated as an emerging research biomarker rather than a validated metric for routine clinical practice.
- **The Detraining Paradox**: Evidence regarding the sustainability of skeletal gains indicates that benefits are highly transient. Most studies report a significant attenuation or complete reversal of BMD gains within 6 to 12 months following the cessation of

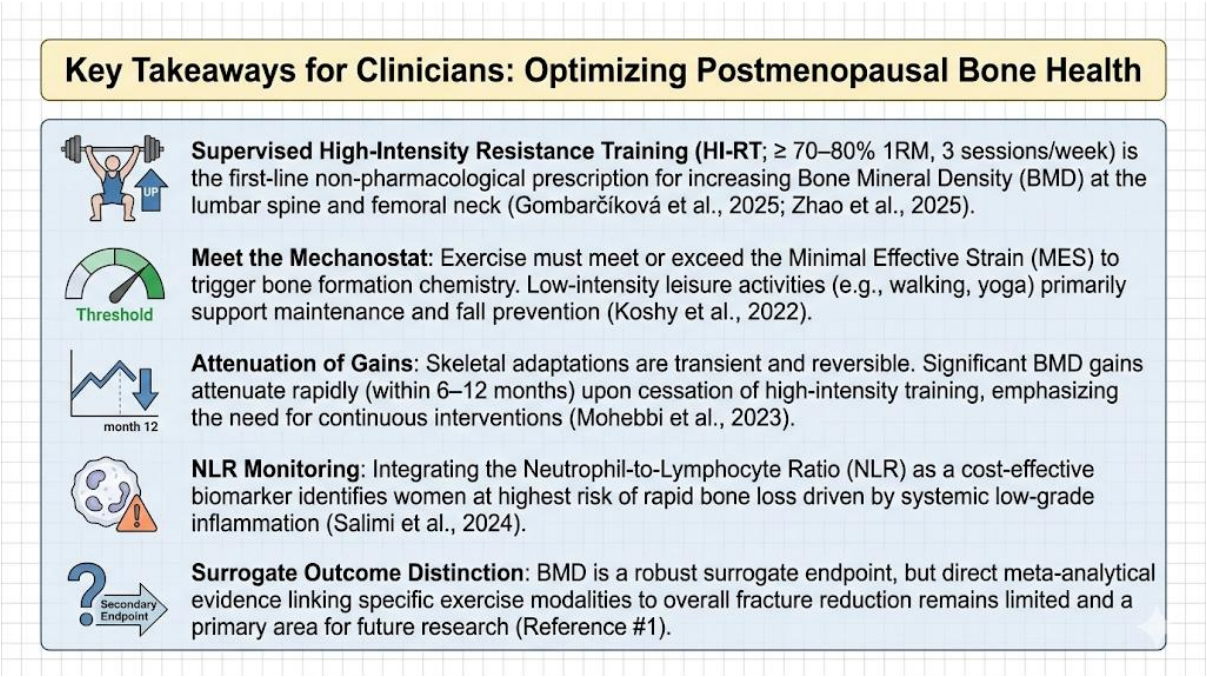
supervised training. This limitation highlights the difficulty in maintaining long-term skeletal adaptations outside of a strictly controlled intervention environment.

6. Conclusions

The synthesis of evidence from 16 systematic reviews, meta-analyses, and randomized controlled trials demonstrates that multi-modal exercise interventions are established non-pharmacological pillars for managing postmenopausal bone health. Structured physical activity offers site-specific benefits, particularly for increasing and maintaining Bone Mineral Density (BMD) at the lumbar spine and femoral neck, which is moderated significantly by training intensity and the presence of professional supervision. High-intensity resistance training (HI-RT) and high-impact loading consistently yield superior skeletal adaptations, while leisure-time and multicomponent activities serve as essential tools for preserving bone mass, suppressing low-grade inflammation (as evidenced by NLR markers), and improving fall-related risk factors.

However, a critical distinction must be drawn between surrogate outcomes and clinical endpoints. While statistically and clinically significant increases in BMD are well-documented following supervised high-intensity protocols, direct evidence for a concomitant reduction in overall fracture incidence remains limited. Most included trials were not adequately powered or of sufficient duration to evaluate actual fracture rate reduction as a primary outcome. Therefore, establish a definitive causal link between specific exercise modalities and fracture reduction is a primary area for future research. Longitudinal, multi-centre trials with extended follow-up are required to confirm that exercise-induced BMD gains translate to substantial decreases in skeletal fragility.

Figure 5: Key Takeaways for Clinicians: Optimizing Postmenopausal Bone Health



Disclosure

Authors' contribution

Conceptualization: Anna Polakowska; Methodology: Anna Polakowska, Wiktoria Sobczak; Check: Alicja Pyzik, Kamil Pielusiński; Formal analysis: Anna Polakowska; Investigation: Anna Polakowska, Alicja Pyzik, Kamil Pielusiński; Writing - rough preparation: Anna Polakowska; Writing - review and editing: Alicja Pyzik and Wiktoria Sobczak; Visualization: Anna Polakowska, Alicja Pyzik; Supervision: Anna Polakowska.
All authors have read and agreed with the published version of the manuscript.

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Institutional Review Board Statement

Not applicable

Informed Consent Statementt

Not apllicable

Conflict of Interest

The authors declare that there are no financial or personal relationships with other people or organisations that could inappropriately influence (bias) the work presented in this review. Specifically:

- No author has received fees for consulting or as a member of a speakers' bureau from companies manufacturing osteoporosis medications or exercise equipment.
- No author owns stocks or shares in companies that may be affected by the publication of this manuscript.
- The authors have no non-financial interests (such as personal or professional relationships) that might be perceived as influencing the objectivity of this report.

Declaration of generative AI and AI-assisted technologies in the writing process.
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Institutional Review Board Statement

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References

1. Zhao F, Su W, Sun Y, Wang J, Lu B, Yun H. Optimal resistance training parameters for improving bone mineral density in postmenopausal women: a systematic review and meta-analysis. *J Orthop Surg Res.* 2025;20(1):523. https://doi.org/10.1186/s13018-025-05890-1
2. Zhang W, Li X, He Q, Wang X. Effects of exercise on bone metabolism in postmenopausal women: a systematic review and meta-analysis of randomized controlled trials. *Front Endocrinol.* 2025;16:1597046. https://doi.org/10.3389/fendo.2025.1597046
3. Manaye S, Cheran K, Murthy C, Bornemann EA, Kamma HK, Alabbas M, et al. The Role of High-intensity and High-impact Exercises in Improving Bone Health in Postmenopausal Women: A Systematic Review. *Cureus.* 2023;15(2):e34644. https://doi.org/10.7759/cureus.34644
4. Schinzel E, Kast S, Kohl M, von Stengel S, Jakob F, Kerschan-Schindl K, et al. The effect of aquatic exercise on bone mineral density in older adults: A systematic review and meta-analysis. *Front Physiol.* 2023;14:1135663. https://doi.org/10.3389/fphys.2023.1135663
5. Mohebbi R, Shojaa M, Kohl M, von Stengel S, Jakob F, Kerschan-Schindl K, et al. Exercise training and bone mineral density in postmenopausal women: an updated systematic review and meta-analysis of intervention studies with emphasis on potential moderators. *Osteoporos Int.* 2023;34(7):1145-1178. https://doi.org/10.1007/s00198-023-06682-1
6. 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. https://doi.org/10.3389/fphys.2023.1105303
7. Wu MC, Nfor ON, Ho CC, Lu WY, Liaw YP. The association between different impact exercises and osteoporosis: an analysis of data from the Taiwan biobank. *BMC Public Health.* 2024;24(1):1881.https://doi.org/10.1186/s12889-024-19403-y
8. Fernández-Rodríguez R, Alvarez-Bueno C, Reina-Gutiérrez S, Torres-Costoso A, Nuñez de Arenas-Arroyo S, Martínez-Vizcaíno V. Effectiveness of Pilates and Yoga to improve bone density in adult women: A systematic review and meta-analysis. *PLoS ONE.* 2021;16(5):e0251391.https://doi.org/10.1371/journal.pone.0251391
9. Gombarčíková T, Svobodová L, Svobodová A, Gimunová M. The effect of physical activity intervention and detraining on postmenopausal osteopenia and osteoporosis: a systematic review. *Front Sports Act Living.* 2025;7:1655404. https://doi.org/10.3389/fspor.2025.1655404
10. Alghadir AH, Gabr SA, Iqbal A. Concurrent effects of high-intensity interval training and vitamin D supplementation on bone metabolism among women diagnosed with osteoporosis: a randomized controlled trial. *BMC Musculoskelet Disord.* 2025;26(1):381. https://doi.org/10.1186/s12891-025-08275-x
11. Chang CF, Lee JI, Huang SP, Geng JH, Chen SC. Regular Exercise Decreases the Risk of Osteoporosis in Postmenopausal Women. *Front Public Health.* 2022;10:897363. https://doi.org/10.3389/fpubh.2022.897363
12. Salimi M, Khanzadeh M, Nabipoorashrafi SA, Seyedi SA, Yaghoobpoor S, Brismée JM, et al. Association of neutrophil to lymphocyte ratio with bone mineral density in post-menopausal women: a systematic review and meta-analysis. *BMC Women's Health.* 2024;24(1):169.https://doi.org/10.1186/s12905-024-03006-1

13. Siyahtaş A, Sayın EÜ, Kurnaz D. The effect of leisure-time physical activities on bone mineral density in postmenopausal women: Systematic review and meta-analysis. *Arch Gerontol Geriatr.* 2026;140:106054. https://doi.org/10.1016/j.archger.2025.106054
14. Koshy FS, George K, Poudel P, Chalasani R, Goonathilake MR, Waqar S, et al. Exercise Prescription and the Minimum Dose for Bone Remodeling Needed to Prevent Osteoporosis in Postmenopausal Women: A Systematic Review. *Cureus.* 2022;14(6):e25993. https://doi.org/10.7759/cureus.25993
15. Shojaa M, von Stengel S, Schoene D, Kohl M, Barone G, Bragonzoni L, et al. Effect of Exercise Training on Bone Mineral Density in Post-menopausal Women: A Systematic Review and Meta-Analysis of Intervention Studies. *Front Physiol.* 2020;11:652. https://doi.org/10.3389/fphys.2020.00652
16. Linhares DG, Borba-Pinheiro CJ, Castro JBP, Santos AOB, Santos LL, Cordeiro LS, et al. Effects of Multicomponent Exercise Training on the Health of Older Women with Osteoporosis: A Systematic Review and Meta-Analysis. *Int J Environ Res Public Health.* 2022;19(21):14195. https://doi.org/10.3390/ijerph192114195
17. Bielecka L. Sports and Bone Health: The Impact of Physical Activity on Bone Mineral Density. Quality in Sport. 2025;37:57211.https://doi.org/10.12775/QS.2025.37.57211
18. Górski S, et al. Sport as one of the preventive factors of osteoporosis - a literature review. Quality in Sport. 2025;48:67092. https://doi.org/10.12775/QS.2025.48.67092
19. Ciułek U, et al. The physical activity in the prevention and treatment of osteoporosis: From biomarkers to quality of life. Quality in Sport. 2024;21:54282. https://doi.org/10.12775/QS.2024.21.54282
20. Ciułek U, et al. The impact of physical activity on menopausal symptoms and health in middle-aged women. Quality in Sport. 2024;53:39901. https://doi.org/10.12775/QS.2024.21.54144
21. Wrona J, et al. The Effect of Resistance Training on Menopausal Symptoms and Bone Health. Quality in Sport. 2026;55:67834. https://doi.org/10.12775/QS.2026.49.67834