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REVIEW ARTICLE

The Impact of Regular Sport Participation on Bone Health and Osteoporosis Prevention

a narrative review

HIGHLIGHTS

- Osteoporosis is a global "silent epidemic" — its incidence is rising with aging populations and sedentary lifestyles, driving substantial healthcare costs.
- Mechanotransduction via osteocytes is the central biological mechanism — sport-induced strain modulates the Wnt/β-catenin and RANKL/OPG pathways and suppresses sclerostin.
- High-impact and multi-directional team sports (basketball, volleyball) are the biomechanical gold standard for stimulating bone modeling across the lifespan.
- High-intensity resistance training (≥80–85% 1RM) is the most effective non-pharmacological intervention for postmenopausal bone loss and male osteoporosis.

- Peak bone mass accrued in youth and fall prevention in old age are the two highest-yield public-health windows; interdisciplinary sport-medicine programs are required.

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ABSTRACT

BACKGROUND: Osteoporosis is a global public health challenge linked to population aging and sedentary lifestyles. Given the limitations of long-term pharmacotherapy, non-pharmacological prevention is essential, with regular physical activity and sport participation holding a paramount position.

AIM: The aim of this study was to review current scientific literature on the impact of regular sport participation on bone health, with emphasis on its role in the prevention and treatment of osteoporosis.

MATERIALS AND METHODS: A review of publications (2021–2026) from PubMed was conducted, including meta-analyses and clinical trials on the relationship between mechanical loading and bone mineral density (BMD).

RESULTS: High-impact and multi-directional sports (volleyball, basketball) provide the most potent osteogenic stimuli. In postmenopausal women, high-intensity resistance training (80–85% 1RM) mitigates bone loss and improves Health-Related Quality of Life (HRQoL). Sport also reduces fall risk in the elderly by enhancing postural stability.

CONCLUSIONS: Regular sport participation is the "gold standard" for osteoporosis prevention. Optimizing peak bone mass in youth and maintaining skeletal integrity in old age are vital. Interdisciplinary collaboration is necessary to implement these findings into public health practice.

KEYWORDS osteoporosis; bone mineral density; sport; resistance training; prevention; quality of life

GRAPHICAL ABSTRACT

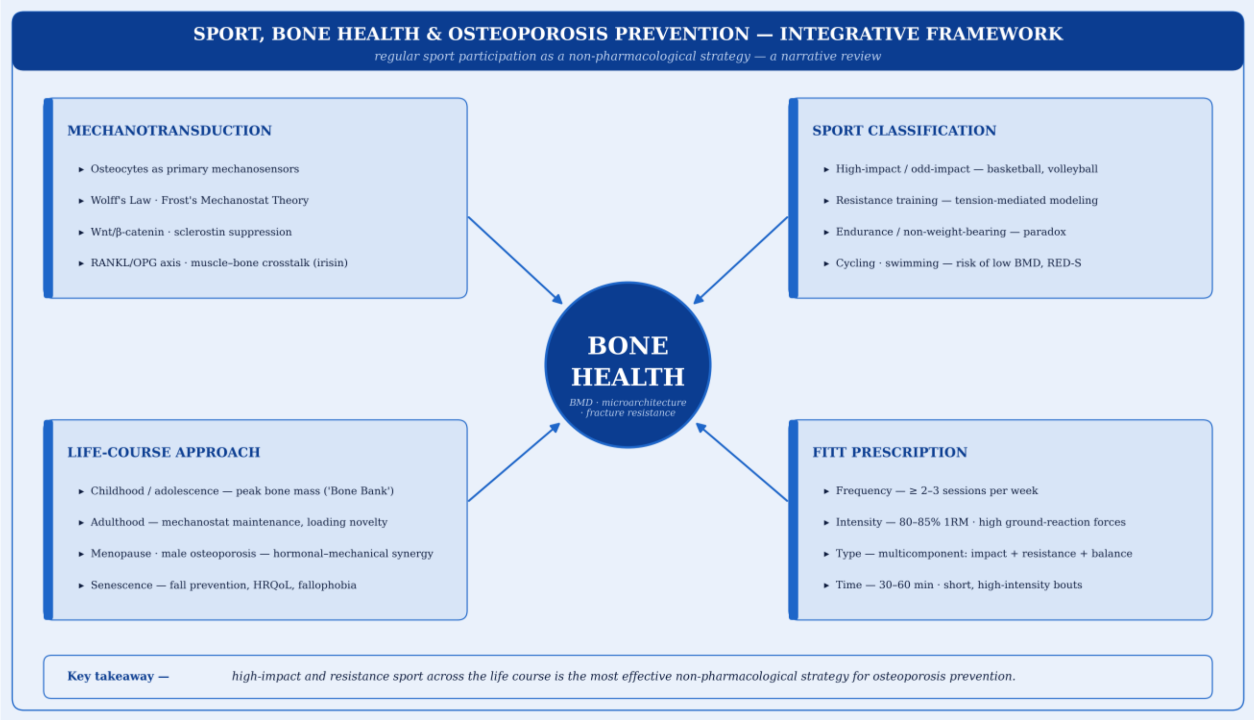

Figure 1. *Conceptual overview of sport, bone health and osteoporosis prevention — mechanotransduction (osteocytes, Wnt/β-catenin, RANKL/OPG), sport classification by osteogenic potential, a life-course approach to skeletal health, and the FITT principle for evidence-based exercise prescription discussed in this narrative review.*

PLAIN LANGUAGE SUMMARY

Osteoporosis makes bones weaker and easier to break, especially as people get older. Drugs help, but they don't fix everything. This review looked at what regular sport does for bones. The short answer: it works — but the kind of sport matters. Activities that pound, twist and jump (basketball, volleyball, running, jumping training) tell bone cells to lay down more bone. Heavy resistance training — lifting weights close to a person's maximum — is the single most reliable way to protect bones after menopause and in older men. Cycling and swimming, even when done at elite level, do not build bone because they remove most of the impact. The biggest gains are in childhood and adolescence, when bone is still growing; the strongest message in older age is that structured, supervised sport with balance and strength work cuts the risk of falling — and falls, not bones alone, are what break hips. Coaches, doctors, physiotherapists and public-health planners should treat sport as a prescription, with dose, intensity and type tailored to age and bone status.

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1. INTRODUCTION

Osteoporosis currently represents one of the most significant global public health challenges, frequently labeled the "silent epidemic" due to its asymptomatic progression until the occurrence of the first fragility fracture. According to recent meta-analyses based on World Health Organization (WHO) diagnostic criteria, the global prevalence of this condition is steadily increasing, a trend closely linked to population aging and sedentary lifestyle shifts (Xiao et al., 2022). The global burden of bone fractures, documented across 204 countries and territories, indicates a drastic rise in clinical incidents, leading to substantial healthcare expenditures and a profound reduction in patients' quality of life (Wu et al., 2021).

Given the limitations and potential side effects of long-term pharmacotherapy, increasing scientific attention is being directed toward non-pharmacological preventive strategies, where regular physical activity and sport participation hold a paramount position. Recent evidence emphasizes that targeted resistance training and structured physical interventions not only mitigate aging-related symptoms but are also crucial for maintaining the structural integrity of bone tissue (Wrona et al., 2026). The impact of sport on bone health extends beyond a simple increase in bone mineral density (BMD); it encompasses complex mechanotransduction processes where bone cells convert mechanical strain into biochemical signals that promote osteogenesis (Li et al., 2021).

The primary objective of this review is to systematically evaluate the current scientific evidence regarding the impact of various sporting modalities on skeletal health. This paper seeks to identify the most osteogenic forms of activity and analyze their efficacy across the lifespan, from maximizing peak bone mass in children and adolescents (Proia et al., 2021) to reducing the risk of falls and fractures in the elderly population (Brooke-Wavell et al., 2022). Understanding the relationship between specific types of athletic loading and the bone's metabolic response is essential for developing effective, evidence-based guidelines for osteoporosis prevention.

2. BIOLOGICAL MECHANISM OF BONE ADAPTATION TO MECHANICAL LOADING

2.1 Mechanotransduction — Osteocytes as Primary Sensors

Mechanotransduction is the fundamental biological process by which physical forces are translated into cellular biochemical responses. In the skeletal system, osteocytes — former osteoblasts trapped within the mineralized lacuno-canalicular system — act as the primary orchestrators of this process (Gardinier, 2021). These cells form an extensive dendritic network that functions as a sensory organ for mechanical strain. When sport-induced loading occurs, it generates interstitial fluid flow within the canaliculi, creating shear stress across the osteocyte membranes (Li et al., 2021). This stress triggers the opening of mechanosensitive ion channels and hemichannels, leading to a rapid influx of calcium ions (Ca^{2+}) and the activation of intracellular signaling pathways. Recent studies emphasize that the "diminishing returns" of mechanical loading observed in elite athletes may be due to the desensitization of these cellular sensors, necessitating varied and novel loading patterns to maintain osteogenic potency (Gardinier, 2021).

2.2 Wolff's Law and the Mechanostat Theory

The functional adaptation of bone is traditionally rooted in Wolff's Law, which posits that bone elements place or displace themselves according to mechanical demands. However, modern bone biology employs Frost's Mechanostat Theory to define specific functional thresholds for these adaptations (Mancuso et al., 2022). Bone tissue operates within four distinct zones: the "disuse window" (leading to resorption), the "adapted window" (homeostasis), the "overload window" (modeling/formation), and the "pathological strain window" (leading to microdamage) (Mancuso et al., 2022). Sport participation aims to consistently reach the "overload window," where dynamic, high-magnitude strains trigger the modeling process, thereby increasing bone mass and optimizing trabecular orientation. Precise mechanical stimuli are required to activate osteoblasts at the periosteal surface, leading to structural reinforcement that reduces fracture risk (Mancuso et al., 2022).

2.3 Molecular Signaling — RANKL/OPG and Sclerostin Inhibition

At the molecular level, exercise exerts its osteogenic effect primarily through the modulation of the Wnt/β-catenin signaling pathway. A key regulator in this process is sclerostin, a glycoprotein secreted by osteocytes that acts as a potent inhibitor of bone formation (Chang et al., 2022). Sclerostin binds to LRP5/6 receptors, preventing Wnt ligands from activating the anabolic signaling required for osteoblast differentiation. Physical activity has been shown to acutely and chronically suppress sclerostin expression, effectively "releasing the brakes" on bone formation (Chang et al., 2022; Oniszczuk et al., 2022). This suppression is a biomarker of osteogenic loading efficacy (Straburzyńska-Lupa et al., 2021). Simultaneously, mechanical loading influences the RANKL/OPG axis — a critical pathway for osteoclastogenesis. Exercise increases the production of osteoprotegerin (OPG), a decoy receptor that binds to RANKL, thereby preventing the activation of osteoclasts and slowing bone resorption (Chang et al., 2022; Hughes et al., 2023).

2.4 Hormonal Synergy and Muscle–Bone Crosstalk

Bone adaptation is not an isolated event but a result of a complex synergy between mechanical loading and the endocrine system. Exercise stimulates the hypothalamic–pituitary–somatotropic axis, increasing the secretion of growth hormone (GH) and insulin-like growth factor 1 (IGF-1), both of which are systemic drivers of osteoblast proliferation (Chang et al., 2022). Furthermore, the emergence of the "myokine theory" has redefined the relationship between muscle and bone. Contracting skeletal muscles act as endocrine organs, secreting myokines such as irisin (Hu et al., 2024; Tsourdi et al., 2022). Irisin promotes the browning of adipose tissue and directly enhances osteoblast activity while suppressing osteoclastogenesis through the downregulation of RANKL. This muscle–bone crosstalk ensures that as muscle strength increases through sport, bone integrity is proportionally reinforced to withstand the higher forces (Shao et al., 2024).

3. CLASSIFICATION OF SPORTS BY OSTEOGENIC POTENTIAL

3.1 High-Impact and Multi-Directional Sports — the Biomechanical Gold Standard

The capacity of a sporting discipline to induce skeletal adaptation is fundamentally predicated on the magnitude, rate, and frequency of the mechanical strain it imposes on the bone matrix. High-impact sports, which necessitate rapid, explosive movements such as jumping, sprinting, and abrupt decelerations, provide a potent osteogenic stimulus by generating ground reaction forces that significantly exceed the thresholds required for bone modeling (Shao et al., 2024). Within this context, team sports like basketball and volleyball are considered exceptionally effective, as they involve "odd-impact" loading — stochastic and unpredictable patterns of strain that prevent the desensitization of osteocytes, thereby maximizing the anabolic response of the bone tissue (Ng et al., 2023). Long-term observational studies, such as the Bunkyo Health Study, have demonstrated that the skeletal benefits of participating in these high-impact activities during the adolescent "window of opportunity" are remarkably persistent, manifesting as significantly higher bone mineral density (BMD) in the femoral neck and lumbar spine even several decades later (Otsuka et al., 2023; Florence et al., 2023). Furthermore, systematic evaluations comparing elite athletes across various disciplines consistently reveal that those engaged in high-impact team sports exhibit superior bone microarchitecture and mineral content relative to their peers in endurance-based or low-impact sports (Zouhal et al., 2024; Imeri et al., 2023).

3.2 Resistance Training — Tension-Mediated Modeling and Muscular Pull

While impact-based activities rely on external forces, resistance training (RT) utilizes high-magnitude internal tension generated by muscular contractions to stimulate bone apposition. This osteogenic effect is primarily mediated by the mechanical pull exerted on the periosteal surface at the sites of muscular insertion, which triggers localized modeling and increases the cross-sectional area of the bone (Massini et al., 2022). For clinical populations — particularly postmenopausal women experiencing rapid estrogen-related bone loss — high-intensity resistance training (HiRT) has emerged as a critical non-pharmacological intervention. Research published in Quality in Sport confirms that structured resistance protocols not only alleviate distressing menopausal symptoms but are indispensable for preserving skeletal integrity and preventing the onset of osteoporosis (Wrona et al., 2026). Recent network meta-analyses suggest that the effectiveness of RT is dose-dependent, with high-load protocols (exceeding 80% of one-repetition maximum) yielding more substantial gains in BMD at the hip and spine compared to low-load or power-oriented training (Rodrigues et al., 2021; Wang et al., 2023).

3.3 The Biomechanical Paradox — Non-Weight-Bearing Sports

A significant challenge in sports medicine is the "bone health paradox" observed in elite cyclists and swimmers who, despite possessing exceptional cardiovascular fitness, often present with alarmingly low BMD. In the case of professional cycling, the lack of gravitational loading, combined with the prolonged seated position, results in a skeletal environment that frequently falls below the minimum effective strain required for bone maintenance (Hilkens et al., 2023). Similarly, the buoyant environment of swimming eliminates the impact forces necessary for osteogenesis, leading to a BMD profile that may be comparable to, or even lower than, that of sedentary individuals (Freitas et al., 2024). This risk is further compounded in endurance athletes by the prevalence of Low Energy Availability (LEA), which can lead to Relative Energy Deficiency in Sport (RED-S), fundamentally undermining the hormonal milieu necessary for bone remodeling (Hutson et al., 2021). To counteract these deleterious effects, it is increasingly recommended that athletes in low-impact disciplines integrate high-impact "bone-loading" microcycles or heavy resistance training to provide the skeletal system with the requisite mechanical stimuli (Florvåg et al., 2025).

4. LIFE-COURSE APPROACH TO OSTEOPOROSIS PREVENTION

4.1 The Pediatric "Bone Bank" — Optimizing Peak Bone Mass during Growth

The longitudinal trajectory of skeletal health is profoundly dictated by the magnitude of bone mineral accretion achieved during the first two decades of life, a phase ontologically recognized as the "Bone Bank" period. Achieving a high Peak Bone Mass (PBM) is considered the most critical primary prevention strategy against geriatric fragility fractures, as approximately 90% of adult skeletal mass is deposited by the age of 20 (Faienza et al., 2023). During the circumpubertal years, specifically during the peak height velocity (PHV) phase, the skeleton is exceptionally sensitive to mechanical loading due to high levels of circulating growth factors and sex steroids. Systematic reviews suggest that participating in high-impact sports such as gymnastics, football, or athletics during this "window of opportunity" induces significant periosteal apposition, thereby increasing the bone's cross-sectional moment of inertia (Zhang et al., 2024). This early-life structural optimization provides a "residual" protective effect; retrospective cohort studies indicate that individuals who were physically active in youth maintain superior cortical thickness and trabecular microarchitecture in late senescence, even after adjusting for current activity levels (Florence et al., 2023; Zouhal et al., 2024).

4.2 Early and Middle Adulthood — Maintenance of the Mechanostat Equilibrium

In the post-PBM phase, the biological objective shifts from the net formation of bone tissue to the rigorous maintenance of existing mineral density and the mitigation of age-related endocortical resorption. During early and middle adulthood, the skeletal system operates within the "adapted window" of the mechanostat, where regular physical activity is required to prevent the transition into the "disuse window," which triggers osteoclast-mediated bone loss (Chang et al., 2022). Academic discourse increasingly emphasizes the importance of "loading novelty"; because osteocytes become desensitized to repetitive, monotonous strain, adult athletes must employ varied loading patterns, such as cross-training and high-intensity intervals, to re-engage the mechanotransduction pathways (Gardinier, 2021; Mancuso et al., 2022). Furthermore, this period is critical for establishing a "musculoskeletal reserve" through resistance training, which counteracts the incipient stages of osteopenia and ensures that the functional muscle–bone unit remains intact as the individual transitions toward middle age.

4.3 The Menopausal Transition and Male Osteoporosis — Hormonal–Mechanical Synergy

The onset of menopause introduces a period of rapid, accelerated bone loss characterized by an uncoupling of the remodeling cycle, where resorption significantly outpaces formation due to the withdrawal of estrogen's inhibitory effect on RANKL expression (Hu et al., 2024). For postmenopausal women, resistance training serves as a potent mechanical surrogate for estrogen, stimulating the Wnt/β-catenin pathway and suppressing sclerostin levels (Oniszczuk et al., 2022; Straburzyńska-Lupa et al., 2021). Recent findings underscore that high-intensity resistance protocols are not only effective in mitigating bone loss at the femoral neck and lumbar spine but also play a transformative role in managing vasomotor symptoms and improving overall metabolic health in this demographic (Wu et al., 2021). Similarly, while often underdiagnosed, male osteoporosis requires targeted interventions; evidence suggests that men with low BMD benefit significantly from high-load impact exercises that stimulate osteoblast proliferation and counteract the age-related decline in bioavailable testosterone and IGF-1 levels (Hu et al., 2023; Bae et al., 2023).

4.4 Senescence, Fall Prevention, and Health-Related Quality of Life

In the geriatric population, the clinical focus of sport participation expands from the preservation of BMD to the holistic prevention of falls, the primary catalyst for catastrophic hip and vertebral fractures (Mohebbi et al., 2023). Multicomponent exercise interventions that integrate progressive resistance training with proprioceptive challenges and dynamic balance exercises have been shown to significantly enhance postural stability and reduce fall incidence by up to 30–40% (Sadaqa et al., 2023; Dyer et al., 2023). Beyond the physiological parameters, regular participation in structured sports programs facilitates "functional independence," allowing older adults to maintain the ability to perform activities of daily living (ADL). Moreover, recent qualitative and quantitative analyses emphasize that sport-based interventions significantly improve Health-Related Quality of Life (HRQoL) by reducing the psychological fear of falling (fallophobia) and fostering social connectivity, which are essential components of successful aging in the context of chronic musculoskeletal conditions (Kenzhegazova et al., 2026; Aleixo and Abrantes, 2024; Hejazi et al., 2022).

5. PRACTICAL APPLICATIONS AND PUBLIC HEALTH PERSPECTIVES

5.1 Evidence-Based Exercise Prescription — the FITT Principle in Osteoprotection

Translating the mechanical principles of osteogenesis into clinical practice requires a structured approach based on the FITT principle (Frequency, Intensity, Type, and Time). For optimal skeletal adaptation, current guidelines suggest a frequency of at least 2–3 sessions per week, with an emphasis on high-intensity protocols (Rodrigues et al., 2021). The "Intensity" component is paramount; to stimulate the mechanostat, loads should reach approximately 80–85% of one-repetition maximum (1RM) in resistance training, or provide ground reaction forces significantly higher than those encountered during daily walking (Wang et al., 2023). Regarding "Type," the evidence favors a multicomponent strategy that combines high-impact loading with heavy resistance training to address both BMD and muscular power (Bae et al., 2023; Mohebbi et al., 2023). The "Time" or duration of these sessions is typically recommended to be between 30 and 60 minutes, as bone cells tend to become desensitized to mechanical stimuli after prolonged, repetitive loading, making shorter, high-intensity bouts more effective than long, low-intensity sessions (Gardinier, 2021).

FITT component	Recommendation	Practical example
Frequency	≥ 2–3 sessions per week, with adequate recovery between high-impact bouts.	Mon / Wed / Fri resistance + Tue or Sat impact session.
Intensity	Resistance training at 80–85% 1RM; impact loading >> daily walking ground-reaction forces.	5 × 5 back squats at 4× body-weight peak; box jumps ≥ 40 cm.

Type	Multicomponent — combine high-impact / odd-impact sport with heavy resistance and balance work.	Basketball or volleyball + heavy compound lifts + single-leg balance drills.
Time	30–60 min per session; favour shorter, high-intensity bouts over long, monotonous sessions.	≈ 45 min sessions; ≤ 30–40 high-impact ground contacts at peak intensity.

Table 1. *The FITT principle applied to osteoprotective exercise prescription — practical targets distilled from current evidence.*

5.2 Safety Considerations — Tailoring Sport for High-Risk Individuals

While sport is a potent preventative tool, its application in individuals with pre-existing osteopenia or a high risk of fragility fractures requires careful clinical modulation. Safety protocols must prioritize the prevention of vertebral and hip fractures by avoiding movements that involve extreme, rapid trunk flexion or forceful spinal rotation, particularly when combined with heavy loads (Brooke-Wavell et al., 2022). For patients with established osteoporosis, a thorough screening — incorporating DXA scans and FRAX scores — is essential before commencing high-impact activities. In these populations, "impact" should be introduced progressively, starting with low-level jumping or stepping exercises, to allow for the gradual adaptation of the bone's structural integrity without exceeding its fatigue limit (Rodrigues et al., 2021; Faienza et al., 2023). Furthermore, the integration of supervised programs ensures that technical execution is optimized, minimizing the risk of traumatic injuries during training.

5.3 Quality of Life — Psychological and Social Dimensions

The public health value of sport-based osteoporosis prevention extends significantly into the psychosocial domain. Participation in structured sporting activities fosters a sense of agency and functional independence, which are critical components of Health-Related Quality of Life (HRQoL) in aging populations (Dyer et al., 2023; Kenzhegazova et al., 2026). Research indicates that group-based interventions significantly reduce "fallophobia" (the fear of falling), a psychological barrier that often leads to social isolation and sedentary behavior in osteoporotic patients (Sadaqa et al., 2023). By improving balance, gait stability, and proprioception, sport empowers individuals to engage more fully in social and community life (Hejazi et al., 2022). As highlighted in recent studies, this social engagement, combined with the physiological benefits of resistance training, creates a synergistic effect that alleviates both physical symptoms and the psychological burden associated with chronic musculoskeletal decline (Wu et al., 2021; Hejazi et al., 2022).

6. DISCUSSION

6.1 Intervention Efficacy — Identifying the "Skeletal Gold Standard"

The synthesis of current evidence confirms a hierarchical structure of osteogenic potential across different sporting modalities, where high-impact and multi-directional activities consistently outperform endurance and non-weight-bearing sports (Ng et al., 2023; Otsuka et al., 2023). While all forms of physical activity contribute to general health, team sports such as basketball and volleyball provide a unique biomechanical stimulus through stochastic "odd-impact" loading, which effectively bypasses the cellular desensitization of osteocytes (Otsuka et al., 2023; Imeri et al., 2023). In contrast, the "bone health paradox" observed in elite cyclists and swimmers, who may exhibit lower bone mineral density (BMD) than sedentary controls, highlights the insufficiency of cardiovascular strain alone to maintain skeletal integrity (Freitas et al., 2024; Hutson et al., 2021; Florvåg et al., 2025). This comparative analysis suggests that for maximum osteoprotection, sporting programs must move beyond simple rhythmic loading toward complex, high-magnitude mechanical perturbations (Sadaqa et al., 2023; Hejazi et al., 2022).

6.2 The Dose–Response Relationship — From Mechanostat to Overtraining

The relationship between sport participation and bone adaptation follows a non-linear dose–response curve governed by the principles of the Mechanostat Theory (Gardinier, 2021; Mancuso et al., 2022). To trigger an anabolic response, the magnitude of strain must exceed the "modeling threshold," typically achieved through high-load resistance training or high-impact maneuvers (Rodrigues et al., 2021; Wang et al., 2023). However, there exists a critical tipping point where excessive training volume, especially when coupled with Low Energy Availability (LEA), leads to the "pathological strain window" and the development of Relative Energy Deficiency in Sport (RED-S) (Florvåg et al., 2025). In this state, the hormonal milieu — characterized by suppressed IGF-1 and sex steroids — undermines the skeletal system's ability to repair microdamage, increasing the risk of stress fractures and accelerated bone loss (Wu et al., 2021; Florvåg et al., 2025).

6.3 Limitations of Current Research and Future Directions

Despite the robust evidence supporting sport as a preventative tool, current literature is frequently limited by its cross-sectional design, which complicates the establishment of definitive causal relationships between specific sport volumes and long-term fracture reduction (Sadaqa et al., 2023; Hejazi et al., 2022). Many studies rely on BMD as a primary surrogate marker, potentially overlooking critical changes in bone quality, such as trabecular microarchitecture and cortical porosity, which are equally vital for structural strength (Ng et al., 2023; Rodrigues et al., 2021). Furthermore, there is a pronounced need for more longitudinal, randomized controlled trials that utilize standardized loading protocols across diverse demographic groups, particularly for older men and individuals with secondary osteoporosis (Bae et al., 2023; Mohebbi et al., 2023).

6.4 Interdisciplinary Collaboration — Bridging Sports Science and Geriatric Medicine

The effective implementation of sport-based osteoporosis prevention requires a paradigm shift toward interdisciplinary collaboration. Public health guidelines must integrate the mechanical insights of sports science with the clinical rigor of geriatric medicine to create "safe-impact" environments for high-risk populations (Wrona et al., 2026). Connecting these fields allows for a more nuanced approach to exercise prescription, where the FITT principle is adapted not only to the patient's BMD score but also to their functional capacity and fracture risk profile (Wrona et al., 2026; Hejazi et al., 2022).

7. CONCLUSIONS

Regular sport participation, particularly in modalities characterized by high-impact and multi-directional loading, constitutes the "gold standard" for non-pharmacological osteoporosis prevention (Ng et al., 2023; Otsuka et al., 2023; Imeri et al., 2023). By optimizing peak bone mass during youth (Faienza et al., 2023; Zhang et al., 2024) and mitigating age-related mineral loss through the activation of mechanotransduction pathways (Gardinier, 2021; Mancuso et al., 2022), sport serves as a lifelong insurance policy for skeletal health. For the aging population, high-intensity resistance training and multicomponent interventions are indispensable tools for reducing the incidence of catastrophic falls (Dyer et al., 2023; Kenzhegazova et al., 2026) and improving Health-Related Quality of Life (HRQoL) (Aleixo and Abrantes, 2024; Hejazi et al., 2022).

From a socio-economic perspective, promoting sport as a primary prevention strategy offers a sustainable solution to the escalating global burden of fragility fractures (Wu et al., 2021) and associated healthcare expenditures. Public health policymakers must prioritize the integration of structured, evidence-based athletic programs into standard clinical practice (Wrona et al., 2026) to foster a resilient, active, and fracture-free society.

5. DISCLOSURE

5.1. Author Contributions

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5.5. Conflict of Interest Statement

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5.6. Data Availability Statement

Not applicable.

5.7. Acknowledgements

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5.8. Declaration of Generative AI Use

AI-assisted tools were used exclusively for linguistic refinement and structural editing of the manuscript. The authors take full responsibility for the scientific content, interpretation of the data, and final version of the manuscript.

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