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Review Article

A Comprehensive Literature Review of the Potential Role of Physical Exercise in Osteoporosis

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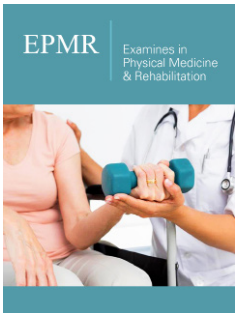

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Abstract

Background: Osteo Porosis (OP) is a metabolic bone disease characterized by decreased bone mass, microstructural deterioration of bone tissue, and increased fracture risk. Given the global aging population, osteoporosis has become a significant public health concern with substantial socioeconomic ramifications. Physical exercise has emerged as a fundamental intervention for the prevention and management of this condition.

Materials and methods: This comprehensive literature review synthesizes evidence from epidemiological studies, clinical trials, and meta-analyses examining the role of physical exercise in osteoporosis prevention and treatment. The literature was sourced from peer-reviewed publications between 1994 and 2025 with an emphasis on high-quality evidence, including randomized controlled trials and systematic reviews.

Result: Regular weight-bearing and resistance exercise has been shown to prevent approximately 2% of annual bone loss in most populations and can increase bone mass by up to 40% in individuals who exercise consistently from an early age. Exercise has been demonstrated to enhance muscle strength, coordination, and balance, thereby reducing the risk of falls by 25-50% in elderly populations. Aerobic exercise has been demonstrated to exert a positive influence on VO2max, body composition, and cardiovascular parameters, while concurrently maintaining bone mineral density. The efficacy of exercise interventions is maximized when they are initiated early in life and consistently maintained throughout the lifespan.

Conclusion: Physical exercise constitutes a safe and cost-effective intervention for the prevention and treatment of osteoporosis. Multimodal exercise programs that incorporate resistance training, weight-bearing activities, and balance exercises have been shown to yield optimal outcomes. Healthcare providers should prioritize exercise prescription in conjunction with pharmacological interventions for the comprehensive management of osteoporosis.

Keywords: Osteoporosis; Physical exercise; Bone mineral density; Fracture prevention; Weight-bearing exercise

Introduction

Osteo Porosis (OP) is a metabolic bone disease characterized by decreased bone mass, microstructural deterioration of bone tissue, and increased susceptibility to fractures [1]. The term “osteoporosis” was first described in 1829 by Jean Georges Lobstein and subsequently defined by Fuller Albright in 1948 as “too little bone in the bone. “Since then, osteoporosis has emerged as one of the most prevalent metabolic bone disorders worldwide [2]. The condition manifests most commonly after the age of 45, with its frequency increasing substantially with

advancing age [1]. As the global population continues to experience an increase in life expectancy, osteoporosis has emerged as a prominent public health concern, affecting approximately 40-55% of women aged 50-60, 75% of women aged 60-70, and 85-90% of women aged 70 and over [3]. The underlying pathophysiology of osteoporosis is characterized by a dysregulation between bone resorption and bone formation. Subsequent to the age of 35, the activity of osteogenic cells undergoes a gradual decline, resulting in a net loss of bone over time. This process is exacerbated by several risk factors, including vitamin D deficiency, sedentary behavior, inadequate nutrition, tobacco consumption, and overindulgence in alcohol [4-6]. Vitamin D deficiency has been identified as a critical modifiable risk factor, with its prevalence being influenced by geographic location, seasonal fluctuations, patterns of sun exposure, age, and cultural practices such as clothing and the use of sunscreen [5,6].

The socioeconomic ramifications of osteoporosis are substantial. In the United States, direct and indirect costs were projected at $21.9 billion in 1998, while healthcare expenses in Sweden amounted to approximately 15.1 million Swedish krona in 2007 [1]. Within the European Union, the annual healthcare expenditures associated with treating femur fractures attributable to osteoporosis approach €4.8 billion [7]. These statistics underscore the pressing need for effective preventive measures and treatment options. An increasing body of research has identified physical exercise as a pivotal element in the management of osteoporosis. In contrast to pharmacological approaches, which primarily influence bone resorption or formation through specific biological pathways, exercise produces pleiotropic benefits for the musculoskeletal system [8]. Mechanical loading during physical activity has been demonstrated to stimulate osteoblast function, enhance muscle strength, improve neuromuscular coordination, and lower fall risk. This multifaceted approach targets multiple dimensions of osteoporosis pathophysiology concurrently [9,10]. The objective of this comprehensive literature review is to synthesize current evidence on the role of physical exercise in the prevention and management of osteoporosis. The review will emphasize the type, intensity, duration, and timing of exercise relative to the progression of the disease.

Materials and Methods

This study employed a comprehensive literature review methodology to assess the extant evidence concerning the impact of physical exercise on the prevention and management of osteoporosis. Peer-reviewed publications released from 1994 to 2025 were carefully sourced from reputable medical databases, including pubmed, psycinfo, sport discus, Cochrane library, and Scopus. The inclusion criteria focused on studies that specifically examined the effects of physical exercise on bone mineral density and fracture risk in populations with varying risk levels for osteoporosis. The data extraction process entailed the identification of pivotal findings from epidemiological studies, clinical trials, and meta-analyses, with a particular emphasis on Randomized Controlled Trials (RCTs) and systematic reviews that provided high-quality evidence. The methodological quality of the studies was assessed using established frameworks, thereby ensuring the credibility of the data. In order to assess the benefits of exercise, a variety of variables were examined, including weight-bearing activities, resistance training, balance exercises, and their consequences for bone density and fall risk. Furthermore, the repercussions of exercise on muscle strength and coordination were incorporated, thereby enhancing the comprehension of its function in the management of osteoporosis. The objective of the review was to delineate effective exercise interventions and promote their integration into clinical practice for the management of osteoporosis.

Result

Bone mineral density outcomes

The relationship between physical activity and bone mineral density has been the subject of extensive investigation across diverse populations. Wolff et al. [11] conducted a meta-analysis of published controlled trials assessing exercise training programs on bone mass. Their findings revealed that exercise interventions prevent approximately 2% of annual bone loss in premenopausal and postmenopausal women, with the exception of instances of rapidly developing bone loss secondary to early menopause or corticosteroid use [11]. While the preservation of bone mass may be regarded as modest in absolute terms, it has been demonstrated to result in clinically significant reductions in fracture risk when sustained over extended periods. The skeletal health of adults has been demonstrated to improve with long-term aerobic exercise, which includes activities such as walking, running, cycling, swimming, and resistance training when performed consistently [11]. It is imperative to note that individuals who engage in regular physical activity during childhood and adolescence, and subsequently maintain an active lifestyle throughout their lives, exhibit significantly greater benefits. The application of dynamic mechanical stress to bones during the process of growth has been demonstrated to result in an increase in peak bone mass of up to 40%, thereby providing a critical reserve that offers protection against age-related bone loss in subsequent decades [12]. The site-specific effects of exercise on Bone Mineral Density (BMD) merit particular attention. Weight-bearing activities primarily influence Bone Mineral Density (BMD) in the lower extremities and axial skeleton, while resistance training with appropriate loading produces localized effects at the exercised sites. As demonstrated in extant research, high-intensity exercise interventions have been shown to have a significant impact on Bone Mineral Density (BMD) at the femoral neck and lumbar spine sites, which are particularly vulnerable to osteoporotic fractures. These findings underscore the necessity of meticulously designing exercise programs that target clinically relevant skeletal regions [13].

Functional outcomes and fall prevention

In addition to its direct effects on bone mass, exercise significantly affects functional outcomes that alter fracture risk. It has been demonstrated that regular physical activity has a substantial

impact on the improvement of muscle strength, coordination, and balance in community-dwelling older adults. This regular physical activity has been shown to lead to a reduction in the incidence of falls by 25-50% among this demographic [14,15]. Sinaki M [15] demonstrated that comprehensive exercise programs addressing multiple domains of physical function yield superior outcomes compared to interventions that focus on single components [15]. The integration of exercises designed to enhance strength, balance, and coordination has demonstrated particular efficacy in the context of fall prevention. Borer KT [16] conducted a systematic review of the evidence linking physical activity to the prevention of osteoporosis in women. The author concluded that exercise plays a crucial role in maintaining bone mass while concurrently enhancing the neuromuscular factors that contribute to falls [16]. This dual mechanism of action preserving skeletal integrity while reducing fall risk positions exercise as distinctly valuable in osteoporosis management. In individuals with established osteoporosis and vertebral fractures, the implementation of exercise programs that are meticulously designed can enhance functional capacity, alleviate pain, and improve quality of life [17].

Cardiovascular and metabolic benefits

The benefits of exercise in osteoporosis extend beyond skeletal health. As reported by Nieman DC [18] regular aerobic exercise has been shown to result in significant improvements in VO2max, defined as the maximum amount of energy an individual can utilize per kilogram of body weight per minute [18]. A body of research has demonstrated that women experiencing natural menopause exhibit positive adaptations to long-term aerobic exercise, including beneficial changes in body weight, body mass index, aerobic and anaerobic power, flexibility, and resting heart rate [19]. Moreau et al. [12] further demonstrated that increasing daily walking distance reduces blood pressure in postmenopausal women, thereby addressing cardiovascular risk factors that commonly coexist with osteoporosis in aging populations [12].

Discussion

Mechanisms of exercise effects on bone

The osteogenic response to mechanical loading is a multifaceted process that involves complex cellular and molecular mechanisms. Osteocytes, the most abundant cells in bone, function as mechanosensory that detect fluid flow within the lacunar-canalicular system and translate mechanical signals into biochemical responses [8]. When subjected to appropriate mechanical strain, osteocytes modulate the activity of osteoblasts and osteoclasts through signaling molecules, including prostaglandins, nitric oxide, and Wnt proteins [9]. This Mechan transduction pathway elucidates the phenomenon that dynamic, high-magnitude loading produces greater osteogenic effects than static or low-intensity activities. The principle of specificity is applicable to exercise-induced bone adaptation. Bone exhibits a heightened response to dynamic loads in comparison to static loads, with high magnitude and rapid application, as well as distribution in unconventional patterns [10]. The underlying principles elucidate the reason why walking, which exerts relatively low-magnitude loads at moderate rates, engenders smaller effects in comparison to jumping or resistance training. Brotzman SB [20] emphasized the effectiveness of a multifaceted exercise regimen comprising weightlifting with the wrists and ankles, in conjunction with stair climbing and stepping, for enhancing bone strength. The quality of the experience is such that it is simply not possible to replicate it through other activities such as cycling or swimming [20].

Exercise prescription considerations

Optimal exercise prescription for osteoporosis requires consideration of disease stage, individual capacity, and safety factors. In early post menopause, when bone loss accelerates, higher-impact activities may be appropriate for appropriately screened individuals without significant fracture risk [13]. However, as osteoporosis advances and fracture risk increases, exercise programs must emphasize safety through fall prevention, postural control, and gradual progression of loading [20]. The frequency, intensity, and duration of exercise required for skeletal benefit have been examined in multiple studies. Generally, weight-bearing activities performed for 30-60 minutes, three to five times weekly, produce measurable effects on BMD when maintained consistently over months to years [11]. Resistance training targeting major muscle groups, performed two to three times weekly with progressive overload, complements aerobic activities by providing site-specific stimulation at clinically relevant skeletal sites [16].

Adherence and patient education

Treatment adherence is a critical determinant of the effectiveness of exercise in the management of osteoporosis. Penning-van Beest [21] reported that adherence rates to osteoporosis treatments, including exercise recommendations, approximate only 50% [21]. Boonen et al. [22] found that patient awareness of the positive effects of calcium and vitamin D nutrients essential for maximizing exercise benefits remains quite low [22]. The hypothesis that educational level may influence adherence patterns remains controversial. Castelo-Branco C [23] reported that patients with low adherence levels had a lower educational attainment than patients with high adherence levels. This finding is in contrast with the results of studies by Vytrisalova et al. [24] Healthcare providers play a pivotal role in promoting exercise adherence through appropriate patient education, realistic goal setting, and ongoing support. A recent study revealed that only a third of physicians adequately inform their patients about osteoporosis management, and four out of five patients do not perceive themselves as being at serious risk [22]. Addressing these knowledge gaps through structured educational interventions, informative meetings, and workshop activities could substantially improve exercise adherence and clinical outcomes [25].

Limitations

This comprehensive literature review is subject to several limitations that must be acknowledged. First, a considerable degree of heterogeneity exists among studies examining the efficacy of exercise interventions for osteoporosis. This heterogeneity

is characterized by variations in exercise protocols, participant characteristics, outcome measures, and follow-up durations. This heterogeneity complicates direct comparisons between studies and limits the precision with which exercise recommendations can be formulated [11]. Secondly, the preponderance of extant evidence is focused on postmenopausal women, with comparatively fewer studies examining the effects of exercise in men, younger populations, or individuals with secondary osteoporosis.

Anderson JJB [26] underscored the significance of initiating primary prevention at an early age to optimize peak bone mass. However, the extant longitudinal data set is deficient in its capacity to thoroughly document the impact of exercise on bone mass accumulation from childhood to late adulthood [26]. Consequently, the extent to which these findings can be extrapolated to diverse populations remains uncertain. Thirdly, the assessment methods employed for bone health demonstrate significant variability across studies. Although Dual-energy X-ray Absorptiometry (DXA) is widely regarded as the gold standard for measuring Bone Mineral Density (BMD), it is important to note that this technique is limited in its ability to capture the full complexity of bone structure and composition. Specifically, DXA fails to fully reflect bone quality, microarchitecture, and material properties [7]. While advanced imaging modalities and biochemical markers may offer complementary information, their utilization in exercise trials remains inconsistent. Fourthly, the duration of the majority of exercise interventions is comparatively brief, particularly when viewed in the context of the lifelong progression of osteoporosis.

Rachner TD [27] observed that osteoporosis is the result of prolonged, incremental bone loss; nevertheless, there is a paucity of studies that have monitored participants for a period exceeding two to three years [27]. The long-term sustainability of the beneficial effects of exercise on bone, as well as the optimal strategies for maintaining adherence over the course of decades, remain incompletely characterized. Finally, confounding factors, including dietary intake, sunlight exposure, medication use, and genetic variations, may influence exercise effects but are rarely controlled adequately in observational studies [28]. Future research should address these limitations through rigorously designed randomized controlled trials with adequate sample sizes, extended follow-up periods, and comprehensive outcome assessment.

Implications for Future Practice and Research

The evidence synthesized in this review identifies multiple directions for future investigation. First, further elucidation is required regarding the dose-response relationships between exercise parameters and skeletal outcomes. While general principles of exercise prescription have been established, precise recommendations regarding optimal intensity, frequency, duration, and progression remain undefined for specific populations [13]. The development of evidence-based prescription guidelines would be greatly informed by randomized controlled trials that methodically and systematically compare various exercise protocols. Secondly, the interaction between exercise and pharmacological interventions warrants systematic investigation. A considerable number of individuals diagnosed with osteoporosis receive bisphosphonates, denosumab, or other bone-active medications in conjunction with exercise interventions [27].

A comprehensive understanding of the potential incremental benefits of exercise in conjunction with pharmacotherapy, and the complementary nature of specific exercise types with particular medications, is essential for the optimization of combination treatment strategies. Thirdly, technological advances have created new opportunities for exercise delivery and monitoring. Digital health interventions, encompassing smartphone applications, wearable devices, and tele-rehabilitation platforms, have the potential to enhance exercise adherence and facilitate personalized prescriptions based on real-time physiological data [25]. Consequently, there is an urgent need for rigorous research that evaluates the effectiveness and cost-effectiveness of technology-enabled exercise programs in osteoporosis management. Fourthly, the role of exercise in special populations necessitates further investigation. Individuals with vertebral fractures, severe osteoporosis, or multiple comorbidities may benefit from adapted exercise programs. However, evidence guiding exercise prescription in these high-risk groups remains limited [17].

Furthermore, the efficacy of exercise interventions for osteoporosis in male non-Caucasian populations and younger adults' merits dedicated investigation. Fifth, implementation science research should examine strategies for translating evidence-based exercise recommendations into clinical practice. Despite the substantial evidence supporting the efficacy of exercise in addressing osteoporosis, significant discrepancies persist between existing recommendations and their practical implementation in real-world settings [22]. A comprehensive understanding of the barriers and facilitators to exercise adoption and maintenance at the individual, provider, and system levels is imperative to inform efforts to disseminate and implement this intervention. Consequently, there is an imperative for economic evaluations of exercise interventions for osteoporosis to inform healthcare policy and resource allocation. While exercise is generally considered cost-effective when compared to many medical interventions, the incorporation of formal cost-effectiveness analyses which would include direct and indirect costs, quality adjusted life years, and long-term outcomes would serve to strengthen the case for the promotion of exercise in the management of osteoporosis [25].

Conclusion

Physical exercise is a critical intervention for the prevention and treatment of osteoporosis, offering benefits that extend beyond skeletal health to encompass functional capacity, fall prevention, and overall well-being. The evidence synthesized in this review demonstrates that regular weight-bearing and resistance exercise prevents bone loss, maintains or increases bone mineral density, improves muscle strength and balance, and reduces fracture risk through multiple mechanisms. The aforementioned benefits are most pronounced when exercise is initiated early in life and

maintained consistently, highlighting the importance of lifelong physical activity for skeletal health. The clinical implications of this evidence are evident: healthcare providers should prioritize exercise prescription as a cornerstone of osteoporosis management, alongside appropriate pharmacological interventions and nutritional optimization. It is imperative that exercise programs be tailored to the individual patient, taking into consideration factors such as age, disease stage, functional capacity, and fracture risk. This personalized approach, which incorporates weight-bearing activities, resistance training, and balance exercises, is crucial in addressing the multifaceted aspects of osteoporosis pathophysiology.

Patient education regarding the benefits of exercise, realistic goal setting, and strategies for maintaining long-term adherence are essential components of effective management. From a public health perspective, the promotion of physical activity across the lifespan is a cost-effective strategy for reducing the burden of osteoporotic fractures in aging populations [29]. Exercise has been demonstrated to have a multifaceted impact on health in older adults. Not only does it play a crucial role in preventing bone loss, but it also has the potential to enhance cardiovascular health, metabolic function, and psychological well-being. This comprehensive approach to health promotion addresses the prevalence of multiple chronic conditions that often coexist in this demographic [30]. Osteoporosis represents a significant public health challenge, particularly in aging populations, as it leads to increased morbidity and healthcare costs due to fragility fractures. Promoting physical activity throughout life has emerged as a cost-effective strategy to mitigate the burden of these osteoporotic fractures, enhancing bone health and overall well-being [29]. Sirtuin 1 (SIRT1), an anti-aging gene, plays a pivotal role in regulating various biological processes, including metabolism and bone remodeling. Recent research suggests that SIRT1 activates osteogenic differentiation and inhibits adipogenesis in mesenchymal stem cells, thereby influencing bone density [31]. Conversely, SIRT1 inhibitors could interfere with these processes, making their consumption critical for osteoporosis prevention [32].

Elevating plasma SIRT1 levels, particularly through targeted exercise regimens initiated early in life, may be essential in reducing the risk of osteoporosis and associated chronic diseases [33]. Understanding the delicate balance between SIRT1 and its inhibitors is fundamental for developing novel preventive and therapeutic strategies against osteoporosis. As global populations continue to age, the importance of exercise as medicine for osteoporosis will only increase. This will require sustained research efforts, clinical attention, and public health investment to realize its full potential in preventing fractures and preserving quality of life.

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Author Contributions

All authors contributed to the conceptualization, literature review, analysis, and writing of this manuscript. All authors read and approved the final version.

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