

## Review Article

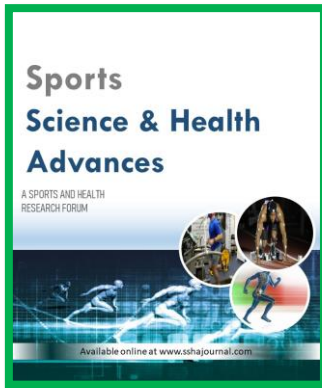
# Optimising Bone Health in Female Athletes: A Narrative Review

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Peer-Reviewed  
Refereed  
Indexed



**How to cite:** Rohilla, R., Therattil, P. (2024). Optimising Bone Health in Female Athletes: A Narrative Review. *Sports Science & Health Advances*. 2(2), 316-321. <https://doi.org/10.60081/SSHA.2.2.2024.316-321>

**Received: 09-12-2024**

**Accepted: 20-12-2024**

**Published: 30-12-2024**



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## Abstract

Bone health is crucial for female athletes to optimize performance, prevent injuries, and ensure long-term well-being. Factors like hormonal changes, nutritional deficiencies, and overtraining can compromise skeletal integrity, increasing risks of stress fractures, osteoporosis, and Relative Energy Deficiency in Sport (RED-S). This review highlights strategies to maintain bone health, focusing on adolescence and early adulthood as critical periods for achieving peak bone mass through weight-bearing and high-impact exercises. The Female Athlete Triad—low energy availability, menstrual dysfunction, and reduced bone mineral density—is a significant risk factor often linked to disordered eating. Nutritional strategies, including sufficient intake of calcium, vitamin D, and balanced diets, are essential for bone health. Exercise interventions like resistance training and plyometrics enhance bone density, while structured training programs with adequate rest reduce cumulative stress on bones. Monitoring menstrual cycles and timely hormonal interventions address menstrual irregularities affecting bone health. Tools like DEXA scans allow early detection of bone density issues, especially in postmenopausal women. Preventive measures, including education and multidisciplinary approaches, help manage conditions like RED-S and promote awareness. Emerging technologies, such as biomarkers and genetic testing, enable personalized care and monitoring. A holistic approach involving collaboration among sports physicians, dietitians, and psychologists ensures optimal bone health, reducing injury risks and supporting athletes' overall well-being across all life stages.

**Keywords:** Bone Health, Vitamin D, Female Athletes, Sports Medicine

## Introduction

Optimal bone health is essential for athletes to achieve peak performance, minimize injury risk, and maintain long-term physical well-being. The repetitive high-impact forces encountered in many sports places considerable stress on the skeletal system, underscoring the critical need for bone resilience. However, factors such as hormonal fluctuations, nutritional deficiencies, and overtraining can significantly compromise bone integrity, predisposing female athletes to conditions like stress fractures and osteoporosis. Notably, female athletes face an elevated risk of conditions such as patellofemoral pain syndrome and

are disproportionately affected by Relative Energy Deficiency in Sport (RED-S), highlighting the necessity for targeted preventive and management strategies (Lin et al., 2018).

### Understanding Bone Health

The skeletal system serves as the framework for the body, providing structural support, safeguarding vital organs, and functioning as levers to facilitate movements. For athletes, robust bone strength is crucial to endure the physical demands of rigorous training and competition. Bone strength, primarily determined by bone mineral density (BMD), is influenced by genetic predisposition, mechanical loading, hormonal regulation, and nutritional status (Nattiv et al., 2007). High-impact physical activities promote bone remodeling and adaptation, while deficits in these factors can compromise skeletal integrity. Notably, women typically exhibit lower bone mass and higher adiposity compared to men and experience an accelerated rate of bone loss with advancing age, emphasizing the need for gender-specific strategies to preserve bone health (Cobb et al., 2007).

### Maximizing Bone Health in Adolescence and Early Adulthood

Childhood and adolescence represent critical periods for establishing lifelong behaviors, including physical activity, that play a pivotal role in preventing osteoporosis later in life. During the two years of peak linear growth, over 25% of adult bone mass is acquired, with bones achieving their maximum density and strength by the end of adolescence. This phase of rapid growth and bone accrual offers a unique window during which weight-bearing exercises and physical activity exert the greatest impact on bone mass and strength. Engagement in recreational activities and competitive sports during childhood significantly enhances bone development. Evidence indicates that children and adolescents who participate in vigorous physical activity exhibit greater bone mass and strength compared to their less active peers. Clinicians should therefore advocate for young patients to engage in at least 60 minutes of moderate to vigorous physical activity daily, incorporating bone- and muscle-strengthening exercises at least three times per week, while limiting sedentary behavior to no more than two hours per day (Zulfarina et al., 2016).

### Risks to Bone Health in Female Athletes

The Female Athlete Triad is a multifaceted medical condition characterized by the interrelationship of three components: low energy availability, menstrual dysfunction, and reduced bone mineral density. This syndrome often arises from inadequate caloric intake relative to energy expenditure, frequently linked to disordered eating behaviours. The resulting hormonal imbalances significantly compromise bone health and overall physiological function. While commonly observed in sports emphasizing a lean physique, such as running, gymnastics, and ballet, the condition can manifest in any physically active female. Studies indicate that approximately 16% of female athletes with this triad exhibit severe impairment across all three domains, underscoring the critical need for early detection and intervention (Grabia et al., 2024).

Low energy availability, whether due to inadvertent caloric insufficiency or secondary to disordered eating (DE) or an eating disorder (ED), disrupts the body's hormonal regulation. Inadequate energy intake impairs the pulsatile secretion of gonadotropin-releasing hormone (GnRH) by the hypothalamus, leading to irregular release of luteinizing hormone (LH) (Loucks & Thuma, 2003) and follicle-stimulating hormone (FSH) (Kluge et al., 2012) from the pituitary. This hormonal disruption reduces estradiol and progesterone production, resulting in menstrual irregularities such as oligomenorrhea and, in severe cases, amenorrhea. Additionally, conditions like polycystic ovary syndrome (PCOS) may further exacerbate hormonal imbalances. Estrogen, a key hormone for preserving bone density, is particularly affected. Lowered estrogen levels elevate the risk of decreased bone mineral density, predisposing females to osteoporosis, bone stress

injuries, and even complete fractures, underscoring the critical need for balanced energy intake and hormonal health in female athletes (De Souza & Williams, 2005).

**Nutritional Deficiencies-** Insufficient intake of essential nutrients, particularly calcium and vitamin D, significantly impairs bone formation and maintenance. Female athletes are especially prone to iron deficiency, which can indirectly compromise bone health by exacerbating low energy availability. This deficiency contributes to osteoporosis, a progressive systemic skeletal disorder characterized by diminished bone mass and microscopical deterioration of bone tissue. These changes increase bone fragility and susceptibility to fractures. Additionally, modifiable lifestyle factors such as physical inactivity, excessive alcohol consumption, smoking, frequent intake of carbonated and processed beverages, and diets high in glycemic index foods further elevate the risk, highlighting the importance of comprehensive preventive strategies (Wasserfurth et al., 2020).

**Relative Energy Deficiency in Sports – Relative Energy Deficiency in Sport (RED-S)**, introduced by the International Olympic Committee in 2014, is a clinical syndrome arising from prolonged or severe low-energy availability. This condition disrupts multiple physiological systems, including energy metabolism, glycogen synthesis, reproductive health, musculoskeletal integrity, immune response, cardiovascular performance, and hematological integrity. These systemic impairments not only elevate the risk of injuries and illness but also significantly compromise athletic performance and overall health, highlighting the critical need for early recognition and targeted management (Mountjoy et al., 2023).

Recognizing athletes with Relative Energy Deficiency in Sport (RED-S) can be challenging due to its diverse and often subtle clinical presentation. Physical manifestations may include disordered eating, alopecia, xerosis, persistent fatigue, unintended weight loss, delayed wound healing, heightened susceptibility to stress fractures, and amenorrhea. Additionally, psychological symptoms such as diminished self-esteem, depressive episodes, and anxiety disorders are frequently observed, underscoring the multifactorial impact of RED-S on both physical and mental health (Jeukendrup et al., 2024).

## Strategies for Optimal Bone Health

### *Nutritional Interventions*

The management of low energy availability involves a structured nutritional plan aimed at reversing energy deficit, achieving a BMI greater than 18.5 kg/m<sup>2</sup>, and maintaining a minimum energy intake of 2,000 kcal/day. The dietary approach should emphasize a balanced intake of carbohydrates, fats, proteins, and essential micronutrients. Calcium supplementation should range from 1,300 to 1,500 mg/day, alongside vitamin D supplementation of 600–800 IU/day, targeting serum vitamin D levels of 32–50 ng/ml. Dietary sources should include dairy products, fortified plant-based alternatives, and green leafy vegetables, complemented by adequate sunlight exposure or supplementation. Additionally, ensure sufficient intake of magnesium, zinc, and vitamin K, all of which play critical roles in bone metabolism.

### *Role of Strength and Resistance Training*

Incorporating weight-bearing and resistance exercises strengthen bones by stimulating bone remodeling. Activities like weightlifting, plyometrics, and running are particularly effective. Charles Turner's three rules for bone adaptation to mechanical stimuli (Turner, 1998) are as follows:

1. Bone adaptation is driven by dynamic rather than static loads.
2. Only a short duration of loading is needed to initiate bone adaptation.
3. Bone cells accommodate and become less responsive to routine loading.

Exercise prescriptions aimed at optimizing bone health across the lifespan should adhere to these three fundamental principles. An effective exercise program has the following features:

- **Frequency:** Regular engagement in weight-bearing activities is essential for promoting bone health.
- **Intensity:** High-impact exercises or activities that generate substantial muscle strain on bones are significantly more effective in stimulating bone adaptation compared to low-intensity exercises.
- **Duration:** Short, intermittent bouts of activity lasting 5–10 minutes, interspersed with rest periods, yield greater benefits for bone remodeling than continuous sessions of equal cumulative load.
- **Type:** Exercises involving multidirectional and varied loading patterns are superior to those with repetitive strain distributions, as they better enhance bone strength and resilience (Kraemer et al., 2003).

### **Balance training**

Progressive balance training involves standing and dynamic exercises with a systematic reduction in the base of support, eventually progressing to single-leg stance. These activities incorporate perturbations to the center of mass through controlled leaning and reaching, followed by regaining balance with minimal reliance on upper extremity support. Further progression includes modifying surfaces (e.g., foam mats) and further reducing the base of support, along with heel-to-toe walking, walking with elevated arms, and withdrawing visual input during balance tasks. Dual-tasking exercises, such as performing cognitive tasks (e.g., counting backward or naming animals) simultaneously with balance activities, enhance stability. When performing tasks with eyes closed, they should be conducted near a secure railing or other stable support to ensure safety. Supervision is essential for frail individuals to minimize the risk of falls during balance training (Wayne et al., 2010).

### **Importance of Menstrual Cycle Monitoring**

Regular menstrual cycles are a marker of optimum hormonal health. Monitoring and addressing any irregularities early can help prevent long-term consequences for bone density. In the diagnosis of amenorrhea, the most important is to rule out pregnancy, thyroid disorders, disorders of the pituitary, ovary, or other endocrine diseases. Treatment of amenorrhea is hormonal replacement therapy or oral contraceptives (Williams et al., 2001).

### **Structured Training Programs**

Structured training programs with adequate rest and recovery periods reduce the risk of chronic stress on bones and ensure proper adaptation. Structured periodization, alternating between phases of high intensity, moderate intensity, and active recovery, prevents cumulative fatigue and overuse injuries. Scheduling regular rest days and recovery weeks is critical to allow musculoskeletal repair and adaptation. Utilize tools like heart rate monitors, GPS trackers, or athlete diaries to ensure training volumes are progressive but manageable. Pay attention to signs of overtraining, such as persistent fatigue, decreased performance, mood changes, or disrupted sleep patterns.

### **Regular Bone Health Assessments**

After the age of 40, bone mass decreases at an average rate of approximately 0.5% per year across all ethnicities, with a notably accelerated decline in women following menopause. Regular evaluation of bone mineral density (BMD) through modalities such as dual-energy X-ray absorptiometry (DEXA) is critical for the early detection and management of bone health deterioration (Zylstra et al., 2008).

### **Preventive measures**

Primary prevention focuses on addressing gaps in awareness and knowledge regarding health, performance consequences, and sports nutrition among athletes and their support networks, including coaches, parents, and performance teams. Secondary prevention

emphasizes the prompt recognition and management of early signs or symptoms to enable timely intervention, thereby averting the progression to more severe outcomes. Effective strategies for identifying at-risk athletes include the use of self-reported screening tools, individualized health interviews, and objective evaluation of relevant biomarkers (Waldrop, 2005).

### *Multidisciplinary Approaches* (Nebigh et al., 2023)

Research highlights the effectiveness of a team-based approach involving sports physicians, dietitians, endocrinologists, physiotherapists, and psychologists, ensuring holistic management of athletes at risk for bone health issues. The inclusion of psychological counseling in sports programs addresses disordered eating and body image concerns, which are closely linked to bone health. Advanced wearable devices and software applications are being developed to track energy expenditure, intake, and recovery in real time, aiding in the prevention of Relative energy deficiency in sports. Increased awareness and education about the Female Athlete Triad and RED-S have improved early detection rates.

### *Emerging Biomarkers for Bone Density Monitoring*

Technology advancements have introduced non-invasive biomarkers and genetic testing to assess bone turnover and predict risks of bone-related conditions, aiding in personalized care for athletes. Recent studies have identified specific biomarkers, such as osteocalcin and C-terminal telopeptide (CTX), that can provide insights into bone turnover rates. These markers help in early identification of individuals at risk for bone-related injuries. Advanced hormonal profiling is being used to detect imbalances contributing to menstrual irregularities and reduced bone density. Research has emphasized the role of optimal vitamin D levels in bone remodeling and healing, leading to a focus on supplementation protocols tailored to athletes' unique needs.

### **Conclusion**

Regular weight-bearing physical activity is fundamental for optimizing bone mass and strength accrual during childhood and adolescence, maintaining these gains throughout adulthood, and mitigating bone loss in later life. High-impact physical activities, even in brief sessions, are particularly effective in promoting bone mass and strength in children and adolescents. Multicomponent exercise regimens that combine progressive resistance training with impact-loading exercises are recommended for individuals across all risk levels—low, moderate, or high—for osteoporotic fractures. Management of conditions such as the Female Athlete Triad or Relative Energy Deficiency in Sport (RED-S) requires a multidisciplinary approach due to the complexity of these issues. Prolonged low energy availability can adversely affect health, contributing to cardiovascular, endocrine, reproductive, skeletal, renal, gastrointestinal, and central nervous system dysfunctions. Early detection and timely intervention in female athletes with RED-S are crucial to prevent long-term health consequences and optimize overall well-being.

### *The Path to Sustainable Athletic Success*

Bone health is a cornerstone of athletic performance and long-term wellness for female athletes. By addressing risk factors such as nutritional deficiencies, hormonal imbalances, overtraining, and implementing strategies for care, athletes can achieve their goals without compromising their health. Education, early intervention, and regular monitoring are key to protecting and enhancing bone health, ensuring both immediate success and a sustainable athletic career.

**Conflict of Interest:** The authors stated no conflict of interest.

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