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RED-S IN ENDURANCE ATHLETES — SKELETAL CONSEQUENCES OF CHRONIC LOW ENERGY AVAILABILITY

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ABSTRACT

Background. Relative Energy Deficiency in Sport (RED-S) is an increasingly recognized health problem among endurance athletes. The main mechanism leading to the development of RED-S is low energy availability (LEA), resulting from insufficient energy intake in relation to exercise energy expenditure. Chronic energy deficiency may lead to hormonal, metabolic and regenerative disturbances, as well as impaired bone health and an increased risk of stress fractures.
Aim. The aim of this review was to summarize current knowledge regarding RED-S in endurance athletes, with particular emphasis on the impact of low energy availability on bone health and the risk of stress fractures.
Material and methods. This review was based on an analysis of scientific literature available in PubMed and Google Scholar databases. Publications concerning RED-S, low energy availability, bone health, hormonal mechanisms, and stress fractures in endurance athletes were included. The analysis included review articles, observational studies, cross-sectional studies, and expert consensus statements published mainly between 2014 and 2026.
Results. The analyzed studies indicate that chronic LEA contributes to disturbances in the hypothalamic–pituitary–gonadal axis, reduced sex hormone concentrations, increased cortisol levels, and decreased IGF-1 concentrations. These hormonal alterations negatively affect bone remodeling processes, leading to decreased bone mineral density and increased susceptibility to bone stress injuries and stress fractures. Female athletes with menstrual disturbances and adolescent athletes during the period of peak bone mass acquisition appear to be particularly vulnerable. RED-S affects both elite and recreational athletes.
Conclusions. RED-S constitutes a significant health concern in endurance sports. Early identification of LEA symptoms, appropriate nutritional support, and proper training load management are essential for preventing long-term bone complications. Multidisciplinary care and education of athletes, coaches, and healthcare professionals play a key role in the prevention and management of RED-S.

KEYWORDS

Relative Energy Deficiency in Sport, RED-S, Low Energy Availability, Endurance Athletes, Bone Health, Stress Fractures, LEA

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1. Introduction

Relative Energy Deficiency in Sport (RED-S) is a condition that particularly affects endurance athletes, especially long-distance runners, triathletes, and cyclists [1,2]. The problem is often associated with dietary restrictions and insufficient energy intake in relation to the energy expenditure required for training and normal physiological functioning [3].

The term RED-S was introduced by the International Olympic Committee as an extension of the Female Athlete Triad, which originally included eating disorders, menstrual dysfunction, and low bone mineral density [1]. Over time, the concept has been expanded to include a broader range of health consequences related to chronic low energy availability, including hormonal, metabolic, immunological, and recovery-related disturbances [4].

The effects of RED-S on bone health are considered particularly important. Long-term energy deficiency may disrupt hormonal balance, impair bone remodeling, and contribute to reduced bone mineral density and an increased risk of stress fractures [4,5]. Bone stress injuries are commonly observed in endurance athletes and may significantly limit physical activity and athletic performance [5,6].

Female athletes with menstrual disturbances and young athletes during the period of peak bone mass development appear to be especially vulnerable to bone-related complications [7]. At the same time, increasing attention is being paid to RED-S in male athletes, although symptoms in men are often less obvious and therefore more difficult to identify [2].

The aim of this study was to present current knowledge regarding RED-S in endurance athletes, with particular emphasis on the effects of low energy availability on bone health and the risk of stress fractures.

Research Objective

The objective of this study was to review current literature concerning Relative Energy Deficiency in Sport (RED-S) in endurance athletes, with a particular focus on hormonal disturbances, bone health, and the risk of stress fractures associated with low energy availability.

Research Problems

1. How does low energy availability contribute to the development of RED-S in endurance athletes?
2. What hormonal mechanisms are involved in bone health impairment in athletes with RED-S?
3. Which groups of athletes are at the greatest risk of stress fractures related to RED-S?
4. What preventive strategies may help reduce the risk of long-term skeletal complications in athletes with RED-S?

Research Hypotheses

1. Chronic low energy availability contributes to hormonal disturbances that negatively affect bone metabolism in endurance athletes.
2. Athletes presenting symptoms of RED-S are at increased risk of bone stress injuries and stress fractures.
3. Early recognition of RED-S and appropriate nutritional and training interventions may reduce the risk of long-term bone complications.

2. Research materials and methods

2.1. Participants

This is a review study. The analysis primarily included publications from the last 5–10 years, as well as older works considered essential to the development of the RED-S and low energy availability (LEA) concepts. Particular attention was paid to the impact of low energy availability on bone health and the risk of stress fractures in endurance athletes.

2.2. Procedure / Measures / Instruments

The literature review was conducted using the PubMed and Google Scholar databases. The search for publications was carried out between March and May 2026. Combinations of English keywords were used, including: “Relative Energy Deficiency in Sport”, “RED-S”, “low energy availability”, “bone health”, “stress fractures”, “bone stress injuries”, “endurance athletes”, “female athlete triad”, and “functional hypothalamic amenorrhea”.

Full-text publications in English, published mainly between 2014 and 2026, were included in the analysis. Expert opinions, review articles, observational studies, cross-sectional studies, and publications concerning hormonal mechanisms and bone health in athletes were considered. Particular attention was paid to publications of the International Olympic Committee (IOC) regarding RED-S and studies involving endurance athletes.

Publications not directly related to the topic of this study, articles with limited data availability, and studies concerning metabolic or hormonal disorders unrelated to low energy availability were excluded. Literature concerning psychological factors, eating disorders, and prevention of bone stress injuries in athletes was also analyzed.

2.3. Data collection and analysis / Statistical analysis

2.3.1. Statistical Software

No statistical software was used because the study was based on a narrative literature review and did not include original quantitative data analysis.

2.3.2. AI
Artificial intelligence tools were used only for linguistic support and improvement of the academic English language of the manuscript. All literature selection, interpretation of findings, and final conclusions were performed independently by the authors.

2.3.3. Statistical Methods
No statistical analysis was performed due to the narrative review design of the study.

3. Research results

3.1 Mechanisms underlying the development of RED-S and low energy availability
The development of Relative Energy Deficiency in Sport (RED-S) is closely linked to low energy availability (LEA). It constitutes the primary mechanism leading to the metabolic and hormonal disorders observed in athletes [8]. LEA results from an insufficient amount of energy supplied through food relative to energy expenditure associated with physical activity and the body's basic needs [8,9]. Consequently, available energy is used primarily to meet the demands arising from training, while the processes responsible for maintaining homeostasis are compromised.

LEA can develop both intentionally and unintentionally. Some athletes deliberately restrict their calorie intake to reduce body weight or improve athletic performance. However, energy deficits can also develop unintentionally, particularly with high training volumes and insufficient energy intake in the diet [3]. This problem primarily affects endurance athletes, mainly long-distance runners, triathletes, and cyclists, where low body weight is often perceived as a factor contributing to improved performance [2,8].

Restrictive dietary patterns, including low-carbohydrate diets, may contribute to the development of LEA by making it difficult to meet the high energy demands of endurance athletes. Reduced carbohydrate intake may lead to impaired recovery, increased feelings of fatigue, and exacerbation of hormonal disturbances associated with LEA [3]. Additionally, inappropriate dietary strategies may co-occur with eating disorders or an excessive focus on weight control [13].

Under conditions of chronic energy deficiency, the body activates adaptive mechanisms aimed at reducing energy expenditure. This results in an adaptive decrease in resting energy expenditure, dysfunction of the hypothalamic-pituitary-gonadal axis, and reduced levels of sex hormones [4]. In women, this can lead to menstrual disorders or functional hypothalamic amenorrhea, while in men, a decrease in testosterone levels and a decline in physical performance are observed [2,4].

Psychological and environmental factors also play a significant role in the development of RED-S. It has been shown that many athletes lacked sufficient nutritional knowledge, causing them to unconsciously struggle to adjust their caloric intake to their training loads [4]. Attention was also drawn to the aspect of promoting a lean physique. Athletes pointed to environmental pressure to achieve a low body weight and a restrictive approach to training [11]. Similar attitudes were also observed among coaches and members of the coaching staff, which may hinder the early recognition of RED-S symptoms [12].

The co-occurrence of RED-S with eating disorders, exercise addiction, and compensatory eating behaviors is also increasingly emphasized [13]. Fahrenholtz et al. demonstrated that in female endurance athletes, the risk of low energy availability was associated with restrictive eating behaviors and an increased focus on weight control [13]. This may lead to the perpetuation of a chronic energy deficit and increase the risk of further health complications associated with RED-S.

3.2. Hormonal Mechanisms of RED-S
A chronic state of energy deficiency leads to a series of changes in the body, including the endocrine system. These mechanisms aim to reduce the body's energy expenditure in order to maintain basic vital functions. Over the long term, they can lead to numerous health disorders [4,8]. Particular importance is attributed to disturbances in the functioning of the hypothalamic-pituitary-gonadal axis, which affect both reproductive capacity and bone metabolism.

In the course of LEA, one of the first adaptive mechanisms is a reduction in the pulsatile secretion of gonadotropin-releasing hormone (GnRH) by the hypothalamus. This leads to a decrease in the secretion of luteinizing hormone (LH) and follicle-stimulating hormone (FSH), resulting in disturbances in sex hormone synthesis [10]. Loucks and Thuma demonstrated that even a short-term reduction in energy availability can disrupt pulsatile LH secretion in regularly menstruating women [10]. In contrast, chronic energy deficiency can lead to prolonged oligomenorrhea or functional hypothalamic amenorrhea (FHA) [7]. A decrease in estrogen levels negatively affects bone remodeling by increasing bone resorption and reducing osteoblast activity [4]. This is of particular importance in young female athletes who have not yet reached peak bone mass. It has been shown that FHA in young female athletes can lead to impaired bone mass gain and increase the risk of fractures later in life [7,19].

Hormonal changes associated with RED-S in men are discussed much less frequently, though they are increasingly being described. The symptoms of this syndrome present a less characteristic clinical picture than in women [2]. Chronic LEA can lead to decreased testosterone levels, impaired recovery, and reduced physical performance [2].

Hormones involved in the regulation of metabolism and energy balance also play a significant role in the pathogenesis of RED-S. Under conditions of energy deficit, leptin levels decrease; leptin is responsible for conveying information about the body's energy reserves [4]. Lowered leptin levels have an inhibitory effect on the hypothalamic-pituitary-gonadal axis, exacerbating hormonal disturbances associated with LEA. At the same time, an increase in cortisol levels and a decrease in triiodothyronine (T3) and insulin-like growth factor IGF-1 are observed, which further adversely affects the body's anabolic and regenerative processes [4,8].

In the course of RED-S, an increase in cortisol levels is also observed, which has a catabolic effect on bone tissue. Chronically elevated cortisol levels disrupt the balance of bone remodeling by inhibiting osteoblast activity and intensifying bone resorption processes [4]. At the same time, there is a decrease in the concentration of the insulin-like growth factor IGF-1, which physiologically stimulates bone tissue synthesis and the body's regeneration [4,8]. These disorders can lead to a gradual decrease in bone mineral density and a deterioration in its mechanical strength.

A consequence of chronic hormonal disorders associated with RED-S is increased susceptibility to stress-related bone injuries, including stress fractures [5]. It has been shown that endurance athletes with symptoms of low energy availability experienced bone injuries more frequently than athletes without LEA characteristics [9]. Similar observations have been reported in studies of female long-distance runners, in whom the presence of menstrual irregularities and restrictive eating behaviors was associated with an increased risk of stress fractures [15].

A growing body of research also indicates that the effects of RED-S on the skeletal system may persist long-term, even after partial normalization of energy intake and body weight [7]. For this reason, early recognition of LEA symptoms and the implementation of appropriate nutritional and training management are crucial for preventing permanent skeletal complications in athletes.

3.3. Stress Fractures and Overuse Injuries of the Bones

Stress fractures constitute a significant portion of overuse injuries observed in endurance athletes. It is estimated that they account for approximately 10–20% of all injuries diagnosed in sports medicine, and they are particularly common among long-distance runners and triathletes [5,16]. They result from the accumulation of microtraumas that exceed the bone tissue's capacity for regeneration and adaptation to training loads [5,16]. Under normal conditions of bone remodeling, microdamage caused by physical exertion is repaired; however, chronic overloading combined with metabolic and hormonal disorders can lead to the development of a full-blown stress fracture [5].

Endurance athletes are particularly at risk for overuse bone injuries due to high training volume and repetitive mechanical loads on the musculoskeletal system [6,16]. The bones of the lower extremities are most vulnerable to this type of injury, particularly the tibia, metatarsals, femur, and pelvis [5,16]. The risk of bone injuries increases significantly with a sudden increase in training volume or intensity without adequate time for recovery [6].

A significant risk factor for stress fractures is low energy availability and the associated hormonal disturbances characteristic of RED-S [8]. Deficiencies in estrogen and testosterone, as well as reduced IGF-1 levels, lead to a deterioration in bone tissue quality and a decrease in its resistance to mechanical stress [4]. Additionally, chronic energy deficit may limit the body's regenerative capacity and intensify catabolic processes, which increases susceptibility to overuse injuries [4,8].

Studies have demonstrated a clear association between LEA symptoms and an increased incidence of bone injuries. It was observed that elite endurance athletes with characteristics of low energy availability experienced stress fractures more frequently than athletes without LEA symptoms [9]. Similar results were obtained by Wilwand et al., who demonstrated an increased incidence of stress fractures in women scoring high on the LEAF-Q questionnaire, used to assess the risk of LEA in female athletes [15]. The authors also noted a relationship between restrictive eating behaviors, high training volume, and the risk of bone injuries [15].

Women with menstrual disorders and young athletes in the period of reaching peak bone mass are particularly at risk for developing stress fractures [7,14]. Chronic LEA during adolescence can lead to abnormal skeletal development and increase the risk of stress injuries at a young age [14]. In contrast, functional hypothalamic amenorrhea significantly increases the risk of reduced bone mineral density and fractures in young female athletes [7].

Early diagnosis of stress fractures is crucial for reducing the risk of complications and shortening the time to return to sports activity. A comprehensive assessment of the athlete is necessary, including an analysis of training loads, dietary habits, menstrual irregularities, and symptoms suggestive of RED-S [16]. In the prevention of overuse injuries, adequate energy intake, a gradual increase in training loads, and early identification of athletes at risk play a particularly important role [6,16].

3.4. Prevention and Management of RED-S

Early identification of athletes at risk and the implementation of appropriate preventive measures are crucial in the prevention of RED-S. It is particularly important to educate athletes, coaches, and members of the coaching staff about the consequences of chronic low energy availability and the impact of restrictive eating behaviors on health and physical performance [8,18]. In many cases, RED-S symptoms develop gradually and remain unnoticed for a long time or are treated as a natural part of intense athletic training [12].

The fundamental element of RED-S prevention is ensuring an adequate energy supply tailored to the volume and intensity of training. Particular importance is placed on an adequate supply of carbohydrates, which are the primary energy source during endurance exercise [3]. Long-term restriction of carbohydrate intake can lead to impaired recovery, increased fatigue, and exacerbation of hormonal disorders associated with LEA [3]. In the prevention of RED-S, it is also important to monitor body weight, the regularity of the menstrual cycle, and the presence of symptoms of chronic fatigue and decreased athletic performance [8].

An increasingly important role is attributed to screening tools that enable the early detection of athletes at risk of developing LEA. One of the most commonly used questionnaires for women is the LEAF-Q (Low Energy Availability in Females Questionnaire), which allows for the assessment of the risk of disorders associated with low energy availability [15]. Wilwand et al. demonstrated that high scores on the LEAF-Q correlated with an increased incidence of stress fractures in recreational female runners [15].

Proper planning of training loads is also crucial in the prevention of stress-related bone injuries. Warden et al. emphasize that a sudden increase in training volume or intensity may exceed the adaptive capacity of bone tissue and increase the risk of stress fractures [6]. The authors highlight the need for a gradual progression of training loads and ensuring adequate recovery time [6].

The literature also emphasizes the importance of early diagnosis of stress fractures in young athletes and appropriate monitoring of training loads [21].

Particular attention should be paid to young athletes going through puberty. Gould et al. emphasize that chronic low energy availability during adolescence can impair the attainment of peak bone mass and lead to long-term health consequences [14]. For this reason, early diagnosis and nutritional education for young athletes are crucial for the prevention of RED-S and its bone-related complications.

The importance of a multidisciplinary approach to the treatment and prevention of RED-S is also increasingly emphasized. Care for an athlete should involve collaboration between a physician, dietitian, psychologist, physical therapist, and coach [8,16]. It is particularly important to identify eating disorders, compensatory eating behaviors, and exercise addiction, which can hinder effective treatment [13,17]. Henninger et al. demonstrated that among trail runners, symptoms of LEA frequently co-occurred with restrictive dietary strategies and features of exercise addiction [17].

Early diagnosis of RED-S and rapid implementation of nutritional and training interventions can reduce the risk of long-term health complications, including hormonal disorders, decreased bone mineral density, and stress fractures [8]. RED-S prevention should be a key component of care for endurance athletes at both the competitive and recreational levels.

4. Discussion

The issue of Relative Energy Deficiency in Sport (RED-S) has been receiving increasing attention in recent years, particularly among endurance athletes. Initially, the focus was primarily on the female athlete triad, which includes eating disorders, menstrual irregularities, and reduced bone mineral density [18, 19]. However, it is now known that the effects of chronic low energy availability have much broader consequences for the body and affect both women and men [2,8].

An analysis of the available literature indicates that endurance athletes constitute a group particularly vulnerable to the development of LEA and RED-S. High training loads, pressure to maintain a low body weight, and restrictive dietary strategies increase the risk of hormonal and bone disorders [1,2]. Due to the growing interest in competitive sports, this problem is increasingly affecting amateur and recreational athletes. Torstveit and Sundgot-Borgen demonstrated that elements of the female athlete triad were present in both elite female athletes and the control group [18]. This may suggest that disorders associated with low energy availability are not limited solely to professional-level sports.

A significant challenge remains the difficulty in diagnosing RED-S. Symptoms of the syndrome develop gradually and may go unnoticed for a long time by both athletes and coaches [4]. Heikura et al. emphasize that assessing low energy availability is difficult, and many athletes maintain high athletic performance despite the presence of LEA symptoms [11]. This can lead to the downplaying of early symptoms of hormonal disorders or deteriorating bone health.

The impact of RED-S on the bone health of young athletes appears particularly concerning. Puberty is critical for achieving peak bone mass, so a chronic energy deficit can lead to lasting health consequences [8,14]. Atadja et al. emphasize that RED-S-related disorders in young athletes may increase the risk of stress injuries and negatively affect skeletal development [14]. Similar observations were presented by Beck and Drysdale, who highlighted the important role of adequate energy intake and early diagnosis in the prevention of stress fractures in young athletes [21].

The analyzed studies also repeatedly emphasized the association between LEA and an increased risk of stress fractures [9,10]. Hormonal disturbances occurring in the course of RED-S lead to a deterioration in bone tissue quality and a reduction in its resistance to mechanical stress [16]. At the same time, the high training volume characteristic of endurance sports increases the risk of microtrauma accumulation and the development of stress injuries [18].

The contemporary approach to RED-S emphasizes the importance of prevention and multidisciplinary care for athletes. Early identification of LEA symptoms, appropriate nutritional education, and monitoring of athletes' health can reduce the risk of developing long-term bone complications [8,21]. However, further research is still needed on effective diagnostic methods and therapeutic management for athletes with RED-S.

5. Conclusions

Relative Energy Deficiency in Sport (RED-S) is a significant health problem in the world of sports. Low energy availability (LEA) is the primary pathophysiological mechanism leading to the development of RED-S, but not every case of LEA leads to full-blown RED-S. This syndrome affects both endurance athletes and amateur athletes. The disorder is primarily associated with chronic low energy availability. Diagnosing the syndrome remains difficult due to the gradual onset of symptoms and insufficient awareness of the problem within the sports community. The consequences of LEA include numerous hormonal and metabolic changes, as well as impaired recovery processes.

One of the most significant and dangerous consequences of RED-S is changes in bone health. Hormonal disturbances occurring during chronic energy deficit lead to a decrease in bone mineral density and an increased susceptibility to stress injuries and fatigue fractures. Women with menstrual disorders and young athletes in the period of reaching peak bone mass are particularly at risk.

Preventive measures—including adequate energy intake, proper planning of training loads, athlete education, and early identification of individuals at risk—are crucial in reducing the risk of developing RED-S and its skeletal complications. Multidisciplinary collaboration among physicians, dietitians, coaches, and physical therapists in the care of athletes also plays a significant role.

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