NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Quality in Sport. eISSN 2450-3118.

Journal Home Page
https://apcz.umk.pl/QS/index

KWITOWSKA Patrycja, UBYSZ Eryk, MURASZEWSKI Łukasz, MURASZEWSKA Emilia, NIERADKA Kornelia, KRAKOWIAK Dominika. The Effects of Relative Energy Deficiency in Sport (RED-S) on Endocrine, Bone, and Metabolic Health and Athletic Performance: A Narrative Review. Quality in Sport. 2026;54:70460. eISSN 2450-3118. https://doi.org/10.12775/QS.2026.54.70460

The journal has been awarded 20 points in the parametric evaluation by the Ministry of Higher Education and Science of Poland. This is according to the Annex to the announcement of the Minister of Higher Education and Science dated 05.01.2024, No. 32553. The journal has a Unique Identifier: 201398. Scientific disciplines assigned: Economics and Finance (Field of Social Sciences); Management and Quality Sciences (Field of Social Sciences).
Punkty Ministerialne z 2019 - aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 l.p. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).
The authors declare that there is no conflict of interest regarding the publication of this paper.
Received: 31.03.2026. Revised: 08.04.2026. Accepted: 08.04.2026. Published: 19.04.2026.

The Effects of Relative Energy Deficiency in Sport (RED-S) on Endocrine, Bone, and Metabolic Health and Athletic Performance: A Narrative Review

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Abstract

Background: Relative Energy Deficiency in Sport (RED-S) is a syndrome caused by low energy availability that impairs multiple aspects of athletes' health and performance. It affects both female and male athletes and may lead to endocrine, bone, and metabolic disturbances, as well as impaired recovery and increased injury risk.

Aim: To review the effects of Relative Energy Deficiency in Sport (RED-S) on athletes' endocrine, bone, and metabolic health, as well as on athletic performance and injury risk.

Material and methods: A narrative review of studies published between 2016 and 2025 was conducted using PubMed, Scopus, and Web of Science to evaluate the effects of LEA and RED-S on endocrine, bone, metabolic, and performance-related outcomes in athletes

Results: RED-S was consistently associated with endocrine and metabolic disturbances, impaired bone health, and a higher risk of bone stress injuries. Evidence for adverse effects on recovery, training adaptation, and performance was also identified, although these findings were more heterogeneous.

Conclusions: RED-S is a multisystem condition that can compromise athletes' endocrine, bone, and metabolic health, with the strongest evidence relating to skeletal health and bone stress injury risk. Early recognition and correction of low energy availability are essential to protect both health and athletic performance.

Keywords: Relative Energy Deficiency in Sport, RED-S, low energy availability, athletes, bone health, endocrine function, metabolic adaptations, injury risk, athletic performance

1. Introduction

Adequate energy availability is one of the fundamental prerequisites for maintaining health and exercise capacity in individuals who participate in sport [1,3]. Under optimal conditions, the energy provided by the diet should cover both the cost of physical activity and the needs associated with basic physiological processes, recovery, and adaptation to training. When energy intake is insufficient relative to energy expenditure, a condition known as low energy availability (LEA) may develop, representing the starting point for further adverse health and performance-related consequences [1,4].

The concept of Relative Energy Deficiency in Sport (RED-S) was introduced by the International Olympic Committee to provide a broader framework for understanding the consequences of chronically reduced energy availability in athletes [1]. In its current

formulation, RED-S is defined as a syndrome of adverse health effects and impaired athletic functioning resulting from problematic low energy availability. Importantly, RED-S affects both women and men, and its clinical presentation extends beyond the previously described concept of the female athlete triad [1,4,7]. Expanding this perspective was necessary because the consequences of energy deficiency encompass far more than menstrual disturbances and reduced bone mineral density alone [1,7,21].

The contemporary understanding of RED-S is multisystemic in nature. Current expert statements and literature reviews indicate that chronic exposure to LEA may affect endocrine, skeletal, metabolic, immune, cardiovascular, and psychological functioning, while also leading to impaired recovery, compromised training adaptation, and reduced competition readiness [1,3,4,7]. It is also emphasized that exposure to LEA is not an all-or-none phenomenon, but rather exists on a continuum—from transient, potentially adaptive changes to a problematic state associated with clinically significant health and performance consequences [1,4].

The importance of RED-S in sports medicine continues to grow. This problem is not limited to a narrow group of athletes, but may occur across many sports disciplines, particularly in endurance, aesthetic, and weight-category sports [1,2,22]. At the same time, increasing attention is being paid to the impact of LEA and RED-S not only on health, but also on athletic functioning, including the ability to sustain training loads, the quality of recovery, and the risk of injury [1–3]. From a clinical perspective, it remains important that there is no single simple, fully validated diagnostic test that enables definitive diagnosis of RED-S; therefore, increasing emphasis is being placed on comprehensive assessment of symptoms, risk factors, and sport-specific context [1,5,6].

Addressing the impact of RED-S on athletes' health appears justified from both a medical and a practical sports perspective. This issue integrates aspects of endocrinology, exercise physiology, sports medicine, clinical nutrition, and injury prevention, and its consequences may affect not only an athlete's current functioning, but also their long-term health [1,3,7]. Given the growing number of publications concerning LEA and RED-S, it is reasonable to organize the current state of knowledge and identify those areas that are best documented, as well as those that still require further investigation [1,2].

The aim of this paper is to review the literature published between 2016 and 2025 concerning the effects of Relative Energy Deficiency in Sport (RED-S) on athletes' hormonal, skeletal, and metabolic health, as well as on their athletic functioning.

2. Material and Methods

This study is a narrative literature review concerning the effects of Relative Energy Deficiency in Sport (RED-S) on health and athletic functioning. Publications from 2016 to 2025 were analyzed in order to base the review on current original studies, review articles, and consensus statements addressing low energy availability (LEA) and RED-S [1–3,7].

The literature search was conducted in the PubMed, Scopus, and Web of Science databases. Keywords and their combinations included, among others: "Relative Energy Deficiency in Sport," "RED-S," "low energy availability," "athletes," "bone health," "endocrine function," "metabolic consequences," "injury risk," and "performance." In addition, the references cited in publications considered key to the topic were also examined [1,2].

The review included English-language publications directly related to LEA or RED-S, involving athletes or highly physically active individuals, and addressing hormonal, skeletal, metabolic, or performance-related consequences. Original studies, narrative and systematic reviews, meta-analyses, and current consensus statements were included [1–3,7]. Publications not directly related to the topic, studies conducted outside athletic populations, as well as case reports and editorial comments, were excluded.

The analysis was qualitative in nature and consisted of a critical synthesis of the data, taking into account hormonal consequences, bone health, metabolic changes, injury risk, and the effects of LEA and RED-S on athletic functioning. Due to the heterogeneity of the studies, differences in LEA definitions, and the assessment tools used, no quantitative analysis was performed [1–3].

3. Pathophysiology of RED-S

Relative Energy Deficiency in Sport (RED-S) results from problematic low energy availability, defined as a state in which the amount of energy provided by the diet is insufficient in relation to the energy expenditure associated with physical activity and the body's basic physiological needs [1,4]. The contemporary understanding of RED-S assumes that the starting point for the development of these disturbances is low energy availability (LEA), which may be either intentional or unintentional [1,4,7]. LEA may arise, among other causes, as a result of dietary restriction, excessive training loads, inadequate planning of energy intake, as well as the coexistence of eating disorders or pressure related to body weight and body composition [1,4,7]. The 2023 IOC consensus emphasizes that exposure to LEA is not an all-or-none phenomenon,

but rather exists on a continuum—from short-term, potentially adaptive changes to a problematic state leading to clinically significant health and performance consequences [1].

Energy availability refers to the amount of energy remaining for the body after subtracting the energy cost of exercise from total energy intake. If this relationship remains unfavorable for a prolonged period, the body activates energy-conserving mechanisms aimed at maintaining the most essential vital functions at the expense of processes considered less urgent from a survival perspective [1,4]. In practice, this means that long-term LEA may lead to suppression of anabolic processes, reproductive disturbances, impaired bone remodeling, alterations in immune response, and reduced training adaptation [1,4,7]. The physiological model proposed by the IOC working group indicates that the development of RED-S is influenced not only by the severity of the energy deficit itself, but also by its duration, the frequency of LEA episodes, the source of LEA, and individual modifying factors such as health status, medical history, dietary patterns, and the nature of training loads [4].

LEA may develop gradually and remain unrecognized for a long time. In some athletes, it results from deliberate restriction of energy intake aimed at reducing body mass or improving the power-to-weight ratio. In others, it is a consequence of underestimating energy requirements during periods of high training volume, frequent competition, or rapid growth and maturation [1,7,24]. For this reason, the pathophysiology of RED-S requires consideration not only of energy balance itself, but also of the training, nutritional, and psychosocial context [1,4,7].

In response to prolonged energy deficiency, the body activates a range of adaptive mechanisms intended to reduce total energy expenditure and preserve functions essential for survival [1,4,7]. These adaptations include, among others, a reduction in resting metabolic rate, changes in the secretion of hormones regulating energy homeostasis, and suppression of processes related to reproduction, growth, and tissue remodeling [1,4]. Within the RED-S model, it is emphasized that the body's response to LEA is systemic in nature and simultaneously affects multiple organs and regulatory axes [4].

One of the key features of these adaptations is their interindividual variability. Not all athletes respond to LEA in the same way or with the same time course. The clinical presentation is influenced, among other factors, by sex, age, stage of maturation, type of sport discipline, dietary composition, training status, and the coexistence of other stressors such as sleep disturbance, illness, psychological stress, or infection [1,4,7]. Thus, the contemporary understanding of RED-S moves away from a simple linear cause-and-effect model and instead

assumes a more complex network of relationships between LEA and its health and performance consequences [4].

One of the earliest described consequences of LEA is endocrine disturbance. Inadequate energy availability may affect the functioning of the hypothalamic–pituitary–gonadal axis, the hypothalamic–pituitary–thyroid axis, as well as systems involved in the regulation of appetite, metabolism, and stress response [1,7]. As a consequence, reductions in sex hormone concentrations, disturbances in thyroid signaling, and changes in leptin, insulin, IGF-1, and cortisol levels may occur [1,7]. Although the exact profile of these disturbances may differ depending on sex and athletic population, the common denominator remains the body's shift into an energy-conserving state in which reproductive and anabolic functions are partially downregulated [1,4,7].

The metabolic consequences of LEA include both reduced energy expenditure and impaired utilization of energy substrates, as well as compromised adaptation to exercise [1,3,4]. Under conditions of prolonged energy deficiency, the body suppresses energy-intensive processes, which may result in slowed metabolism and a shift in physiological priorities [1,4]. In practice, this means reduced energy availability for repair processes, tissue remodeling, and long-term training adaptation. The review by Melin et al. emphasizes that LEA may affect performance both directly and indirectly—through impaired recovery, reduced training response, diminished cognitive function, and increased susceptibility to illness or injury [3].

Not every exposure to LEA leads to fully developed RED-S; however, as the duration of energy deficiency increases and its severity worsens, the risk of developing clinical symptoms also rises [1,4,7]. In this sense, RED-S can be understood as the clinical manifestation of problematic LEA, encompassing multisystem health consequences and impaired athletic functioning [1]. The most important clinical consequences include endocrine disturbances, impaired bone health, increased risk of overuse injuries, reduced exercise capacity, and impaired recovery [1–3,7]. Understanding this mechanism is crucial for the proper interpretation of clinical data and for planning effective prevention and therapeutic strategies [1,4,5].

4. The Impact of RED-S on the Endocrine and Metabolic Systems

Endocrine and metabolic disturbances are among the earliest described and best-substantiated consequences of problematic low energy availability [1,7]. In the contemporary understanding, RED-S is not limited to isolated laboratory abnormalities, but rather constitutes a constellation of coexisting changes involving the hypothalamic–pituitary–gonadal axis, the hypothalamic–

pituitary–thyroid axis, hormones involved in metabolic regulation, and secondary consequences affecting energy homeostasis and potentially the cardiovascular profile [1,7]. The endocrinological consequences of RED-S affect both sexes and result from the body's adaptive response to energy deficiency, leading to suppression of reproductive and anabolic functions in favor of preserving basic vital processes [1,7].

One of the principal hormonal mechanisms in RED-S is suppression of the hypothalamic–pituitary–gonadal axis. In women, this may lead to reduced estradiol concentrations and disturbances in LH and FSH secretion, whereas in men it may result in lower testosterone concentrations and impaired reproductive function [1,7]. At the same time, changes are observed within the thyroid axis, particularly a reduction in fT3, as well as disturbances involving leptin, insulin, IGF-1, and cortisol, reflecting the body's shift into an energy-conserving state [1,7,8].

In the study by Marzuki et al., which included national team athletes, individuals with features of LEA were found to have low estradiol concentrations in 87.5%, low testosterone concentrations in 75.0%, reduced fT3 in 66.7%, and low LH and FSH in 58.3% each [8]. Mean fT3 concentrations were lower in athletes with LEA than in those with optimal energy availability (2.6 ± 1.3 vs 3.9 ± 0.9 pmol/L; $p = 0.006$), as were LH (2.5 ± 1.7 vs 3.5 ± 1.8 IU/L; $p = 0.012$), estradiol (88.0 vs 237.0 pmol/L; $p < 0.001$), and testosterone (13.6 ± 13.1 vs 20.0 ± 5.0 nmol/L; $p = 0.039$) [8]. In logistic regression analysis, fT3, estradiol, and testosterone emerged as significant predictors of LEA, with p-values of 0.012, 0.015, and 0.046, respectively [8].

Studies involving men have also demonstrated detectable endocrine changes associated with RED-S. Moore et al. analyzed male endurance athletes and showed that leptin was strongly positively correlated with body fat percentage both during a week of high training volume and during a week of lower training volume ($r = 0.88$; $p < 0.001$ and $r = 0.93$; $p < 0.001$, respectively) [9]. A moderate positive correlation was also found between testosterone and body fat percentage ($r = 0.56$; $p = 0.05$), a negative correlation between leptin and fat intake ($r = -0.60$; $p = 0.03$), and a negative correlation between testosterone and carbohydrate intake during the high-volume training week ($r = -0.66$; $p = 0.006$) [9]. These findings suggest that an athlete's hormonal response may be modulated not only by total energy intake, but also by the availability of specific macronutrients [1,9,23].

Additional evidence is provided by the experimental study by Jurov et al., in which energy availability was intentionally reduced in trained men. The authors demonstrated that reducing energy availability to 22.4 ± 6.3 kcal/kg FFM/day was associated with decreased hemoglobin concentration ($t(12) = 2.652$; $p = 0.022$), impaired well-being ($t(12) = 2.385$; $p = 0.036$), and a significant association between cognitive restraint and energy availability ($r = 0.528$; $p = 0.039$) [10].

The metabolic consequences of RED-S primarily include a slowing of metabolism, alterations in energy substrate utilization, and secondary modifications in markers related to energy balance [1,7]. In clinical practice, this means that the body reduces energy expenditure on non-priority processes, which may lead to impaired recovery, tissue remodeling, and capacity for training adaptation [1,3,4]. Reviews emphasize the particular importance of reductions in leptin, insulin, IGF-1, and T3 as key elements of the adaptive response to energy deficiency [1,7].

McGuire et al. evaluated highly trained male endurance athletes and showed that mean energy availability was below 30 kcal/kg LBM/day in 76.9% of participants [11]. In this group, mean concentrations of insulin, IGF-1, and leptin were below reference ranges, while signs of increased bone resorption were also observed [11]. These findings fit into the broader picture of RED-S as a condition involving coexisting endocrine and metabolic disturbances, particularly among endurance athletes [1,7,11].

One of the more recent directions in RED-S research has been the assessment of a possible relationship between chronic LEA and lipid profile, and indirectly, cardiovascular risk [7,12]. Silvennoinen et al. analyzed Finnish endurance athletes at the beginning and at the end of the training season. The authors found no significant cross-sectional association between RED-S risk and cholesterol levels; however, in women, an increase in RED-S risk between the beginning and the end of the season was associated with a decrease in LDL cholesterol (age-adjusted beta −0.62; 95% CI −0.94 to −0.30; $p = 0.00049$) and total cholesterol (beta −0.85; 95% CI −1.42 to −0.28; $p = 0.0050$) [12]. After additional adjustment for seasonality, these associations remained significant [12]. These findings should be interpreted with caution, as reduced LDL and total cholesterol concentrations do not necessarily indicate a favorable cardiometabolic effect, but may instead reflect disturbed energy metabolism [7,12].

In summary, the available evidence confirms that the endocrine system and metabolism are among the key domains affected in RED-S. Of particular clinical importance are reductions in

fT3, sex hormones, leptin, and IGF-1, which should always be interpreted in the context of the athlete's overall clinical picture [1,5,7,8].

5. The Impact of RED-S on Bone Health and Injury Risk

Bone health is one of the best-documented domains affected in RED-S [1,2,17]. The current understanding of the problem indicates that chronically low energy availability adversely affects bone metabolism, bone remodeling, bone mineral density, as well as the microarchitectural and mechanical properties of the skeleton [1,17]. In clinical practice, this is of particular importance because the consequences of these changes may include not only reduced BMD, but also an increased risk of bone stress injuries, which in athletes represent a major cause of missed training and competition [1,2,16].

The mechanism underlying these disturbances is multifactorial. Low energy availability leads to hormonal changes that include, among others, reduced concentrations of sex hormones, IGF-1, and thyroid hormones, as well as alterations in leptin secretion and other regulators of metabolism [1,7,17]. The result is a shift in the balance of bone remodeling toward impaired bone formation and increased resorptive processes [1,17]. This means that an athlete, despite a high level of physical activity, does not always obtain the expected protective effect of training on the skeleton [15,17].

In the study by Ikegami et al., involving adolescent female athletes, percentage of ideal body weight was positively correlated with whole-body-less-head BMD ($r = 0.61$; $p < 0.01$), lumbar spine BMD ($r = 0.55$; $p < 0.01$), and trabecular bone score (TBS) ($r = 0.47$; $p = 0.03$) [13]. These findings are particularly important because adolescence is a critical period for bone mass accrual, and disturbances occurring at this stage may have long-term health consequences [13,24].

Smith et al. investigated elite winter sport athletes using HR-pQCT and demonstrated that, after adjustment for lean body mass, athletes at risk of RED-S had a higher likelihood of unfavorable bone parameters [14]. Lower cortical thickness was associated with a greater likelihood of classification into the RED-S risk group both at the radius (OR = 2.1; $p = 0.021$) and the tibia (OR = 1.9; $p = 0.037$) [14]. Similarly, lower cortical area was associated with a higher likelihood of RED-S risk classification at the radius (OR = 3.0; $p = 0.007$) and the tibia (OR = 2.7; $p = 0.006$) [14]. At the tibia, lower total vBMD (OR = 2.1; $p = 0.030$) and lower failure load (OR = 2.2; $p = 0.033$) were also more frequently observed in athletes at risk of RED-S [14].

Valuable data have also been provided by studies in men. Haines et al. showed that male runners with lower energy availability had impaired skeletal integrity compared with non-athletes [15]. The authors emphasized that, despite the loading characteristic of running, lower energy availability offset the potential osteogenic benefits of training [15].

A particularly important clinical consequence of impaired bone health in RED-S is bone stress injury (BSI) [1,2,16]. BSIs encompass a spectrum of changes ranging from bone stress reactions to full stress fractures and are considered among the most serious injuries associated with chronic energy deficiency in athletes [1].

Holtzman et al. analyzed adolescent girls and young women engaged in sport who had sustained bone injuries at either high-risk or low-risk sites [16]. They demonstrated that indicators suggestive of low energy availability were more frequently associated with high-risk injuries ($p = 0.032$), and DXA Z-scores below −1 were also associated with a greater likelihood of high-risk injury ($p = 0.035$) [16]. Moreover, a greater number of coexisting Female Athlete Triad/RED-S risk factors was associated with a higher likelihood of sustaining a high-risk injury ($p = 0.048$) [16].

The meta-analysis by Gallant et al. indicated that the most consistent and best-documented consequences of LEA/RED-S concern deterioration in bone health and an increased risk of BSI [2]. From a practical perspective, the skeletal domain currently appears to be the most clearly clinically validated component of RED-S [2,17].

6. The Impact of RED-S on Athletic Functioning

The impact of RED-S on athletic functioning is one of the most important, yet also one of the more complex, areas of research [2,3]. Compared with skeletal and hormonal consequences, data regarding performance are more heterogeneous, which results from differences across sport disciplines, duration of exposure to LEA, methods used to define energy deficiency, and the exercise tests applied [2,3]. Despite these limitations, the current literature indicates that athletes with LEA more frequently exhibit impaired training response, reduced performance capacity, poorer concentration, impaired coordination, worse decision-making, and a greater risk of missing training due to illness [1–3,20].

In the study by Lundstrom et al., female distance runners were assessed before and after the competitive season and classified on the basis of the RMR_ratio as either metabolically suppressed or energy replete [18]. Athletes with features of impaired energy status achieved a

worse 5-km running time than the group without signs of metabolic suppression (22.4 vs 20.4 min; $p = 0.04$), and this difference persisted throughout the season [18]. Moreover, after controlling for postseason VO_2max, preseason TT_3 concentration was found to be a significant predictor of final 5-km performance ($R^2 = 0.614$; $p = 0.001$) and of the change in performance over the season ($R^2 = 0.455$; $p = 0.014$) [18].

Similar conclusions have been drawn from experimental studies in men. Jurov et al. demonstrated that, in trained endurance athletes, experimentally induced reduction of energy availability to 22.4 ± 6.3 kcal/kg FFM/day led to a significant decline in explosive power ($t(12) = 4.570$; $p = 0.001$) as well as impaired well-being ($t(12) = 2.385$; $p = 0.036$) [10].

It is worth emphasizing that the effect of LEA on performance does not always take the form of a clear decline in all exercise-related parameters. Stenqvist et al. showed that a 4-week period of intensified training in well-trained cyclists increased peak power output (+4.8%; $p < 0.001$), VO_2peak (+2.4%; $p = 0.005$), and functional threshold power (+6.5%; $p < 0.001$), but was simultaneously associated with a decrease in T_3 (−4.8%; $p = 0.008$), a reduction in RMR_ratio (−3.3%; $p = 0.011$), and an increase in cortisol (+12.9%; $p = 0.021$) [19]. This indicates that short-term improvements in performance may coexist with early markers of RED-S-related disturbances [19].

In the review by Melin et al., it was emphasized that inadequate energy availability may reduce the quality of adaptation to exercise loads by limiting repair processes, tissue remodeling, and restoration of energy stores after training [3]. Within this model, an athlete may be able to complete the planned training work, yet fail to achieve the expected improvement in performance because of incomplete recovery and chronic metabolic compensation [3].

In the study by Lundstrom et al., athletes with preseason metabolic suppression did not achieve the same training effect during the season as energy-replete athletes [18]. Stenqvist et al., in turn, demonstrated that participants with a greater increase in the fT:cor ratio achieved a greater improvement in functional threshold power than the remaining athletes (9.5 vs 2.5%; $p = 0.037$), while also showing a more favorable change in relative RMR (0.6 vs −4.2%; $p = 0.039$) [19]. These findings suggest that the hormonal and metabolic response to training load may modulate the effectiveness of exercise adaptation [18,19].

The impact of RED-S on performance is not limited to physical capacity. In the IOC model and in the meta-analysis by Gallant et al., impaired concentration, coordination, judgment, and agility were also listed as consequences of LEA [1,2]. Ackerman et al. showed that low energy

availability, assessed using screening tools, was associated with more frequent self-reported impaired training response, poorer judgment, coordination, concentration, and endurance [20]. The study by Jurov et al. also points in this direction: after experimental reduction of energy availability, athletes reported poorer well-being, and cognitive restraint was significantly associated with the level of energy availability ($r = 0.528$; $p = 0.039$) [10].

In the meta-analysis by Gallant et al., athletes with LEA were found to have a higher rate of training absence due to illness than athletes with adequate energy availability [2]. Increased absence may be one of the most practically relevant manifestations of RED-S, because even if the decline in performance itself is subtle, a greater frequency of training interruptions limits the continuity of athletic preparation [2,3]. Therefore, evaluation of an athlete with suspected RED-S should include not only current sporting results, but also the history of missed training sessions, reduced tolerance to training loads, and difficulties in maintaining the planned competition schedule [1–3].

7. Risk Groups and Predisposing Factors

RED-S may occur in athletes of both sexes, across different age groups, and in many sport disciplines. At the same time, the current literature indicates that the risk of developing problematic low energy availability is not evenly distributed and increases under specific training, nutritional, and psychosocial conditions [1,21,22]. The IOC consensus emphasizes that LEA and RED-S are observed particularly frequently in sports in which low body mass, a lean physique, or a specific body composition are perceived as beneficial for performance, although the problem may also affect athletes outside these categories [1]. The estimated prevalence of LEA/RED-S indicators ranges from 23% to 79.5% in women and from 15% to 70% in men, depending on the population studied and the assessment tools used [1].

One of the most frequently identified high-risk groups is endurance athletes [1,22,23]. In this group, high training volumes, substantial energy expenditure, and the pursuit of lower body mass or an improved power-to-weight ratio promote chronic energy deficiency [1,23]. In practice, this applies particularly to long-distance runners, triathletes, cyclists, and cross-country skiers [1]. Low carbohydrate availability may represent an additional contributing factor. Lodge et al. emphasized that low carbohydrate availability is common among female endurance athletes and may amplify the health and performance consequences of chronic energy deficiency [23].

High-risk groups also include aesthetic sports such as gymnastics, figure skating, dance sport, and diving [1,21]. In these disciplines, pressure to maintain a lean physique, body exposure, and specific appearance-related expectations may promote dietary restriction and reinforce behaviors leading to LEA [1,21]. In such environments, symptoms of RED-S may remain unrecognized for a long time or may be misinterpreted as part of "sporting discipline" [1].

Another high-risk group includes weight-category sports, in which athletes strive to maintain a specific body weight category [1,21]. This includes, among others, combat sports, lightweight rowing, and some strength disciplines. In these sports, periodic or chronic weight reduction may lead to recurrent episodes of LEA, especially if carried out without appropriate nutritional and medical support [1].

Young athletes represent a group at particular risk because their energy needs result not only from training, but also from growth, maturation, and the attainment of peak bone mass [1,24]. Insufficient energy intake during this period may therefore affect not only current athletic functioning, but also somatic development and health in adulthood [1,13,24]. A review addressing nutrition in young athletes emphasized that LEA is one of the major nutritional risks in this group, and that its consequences may be particularly significant precisely because training overlaps with biological development [24].

The contemporary understanding of RED-S clearly moves away from treating this problem solely as a female issue [1,7]. The IOC consensus emphasizes that RED-S affects both women and men, although the clinical presentation and the way the problem is identified may differ between the sexes [1]. Available data nevertheless suggest that the risk may be higher in women. In the study by Marzuki et al., RED-S risk was identified in 41.2% of women and 26.0% of men [22]. At the same time, more recent studies conducted in men indicate that the problem in this group is probably underestimated. Holtzman et al. showed that RED-S risk is also common among men presenting for medical care, and that low BMI may not be a good predictor of the presence of the problem [25].

One of the most important predisposing factors for RED-S is pressure related to body weight and body composition [1,21,22]. This pressure may arise from the demands of the sport itself, coaching expectations, environmental norms, the athlete's self-evaluation, or the belief that lower body mass will automatically improve performance [1]. Such pressure may lead to energy restriction, irregular eating, chronic calorie "monitoring," and overly aggressive attempts to reduce body fat [1,22].

The primary causal factor in RED-S remains problematic low energy availability [1]. In recent years, however, increasing attention has also been paid to the quality of energy intake, especially carbohydrate availability [23,26]. Vardardottir et al. showed that, in female athletes, different patterns of energy availability and carbohydrate intake were associated with varying severity of RED-S symptoms, supporting the hypothesis that chronically low carbohydrate intake may exacerbate the effects of problematic LEA [26].

8. Clinical Management, Prevention, and the Importance of Early Recognition

Clinical management of RED-S is based primarily on recognizing the problem as early as possible, performing a comprehensive assessment of the athlete's condition, and treating the underlying cause, namely problematic low energy availability [1,5–7]. The aims of management are to improve the athlete's health, reduce the risk of irreversible consequences, and safely maintain or restore the ability to train and compete [1,7,27].

Early identification of athletes at risk of RED-S is of key importance because symptoms often develop gradually and may initially be nonspecific [1]. Warning signs include, among others, chronic fatigue, reduced training tolerance, menstrual disturbances, recurrent overuse injuries, unintentional weight loss, decreased libido, chronic gastrointestinal problems, and mood changes [1,7]. The most appropriate times for risk screening are periodic pre-participation evaluations, the beginning of the training season, the return-to-play period after injury, and situations in which there is a marked change in body mass, training load, or dietary practices [1,5].

Given the complex nature of RED-S, an interdisciplinary approach is recommended [1,7,27]. The optimal model of care involves collaboration among a physician, sports dietitian, psychologist or psychiatrist, physiotherapist, and coach, with the composition of the team tailored to the athlete's clinical presentation [1,27]. This model is particularly important when LEA coexists with eating disorders, body image disturbances, chronic psychological stress, or recurrent injuries [1,7,27].

At present, the most important tool supporting risk assessment is the IOC REDs CAT2 [5,6]. This tool is based on a three-step approach: screening, severity assessment and risk stratification, and decision-making regarding clinical management and sport participation [5,6]. In practice, it is intended to help organize information obtained from medical history, physical examination, additional investigations, and observation of the athlete's functioning [5,6]. A

four-level traffic light risk classification has also been emphasized, including the green, yellow, orange, and red categories [6,27].

The cornerstone of RED-S treatment remains correction of energy availability [1,7,27]. Treatment should primarily be non-pharmacological and aimed at eliminating the cause of energy deficiency, namely by increasing energy intake, reducing training energy expenditure, or combining both strategies [1,7]. Nutritional intervention should be individualized and should take into account total energy intake, meal distribution, carbohydrate availability around training, adequacy of protein intake, and hydration status [1,7,23]. At the same time, modification of training loads is also important [1,5,27]. In athletes with symptoms of RED-S, a temporary reduction in training volume and intensity may be necessary, particularly when overuse injuries, significant hormonal disturbances, impaired recovery, or systemic symptoms are also present [1,27].

Prevention of RED-S is based primarily on the education of athletes, coaches, and members of the medical support team [1,28]. A systematic review of educational interventions emphasized that strategies focused on nutritional knowledge and awareness of LEA may help reduce behaviors leading to chronic energy deficiency [28]. Preventive measures should also include fostering a safe training culture, avoiding pressure toward excessive weight loss, promoting adequate nutrition around training, and regularly monitoring health status [1,28].

9. Discussion

The literature analysis conducted indicates that RED-S should be regarded as a multisystem clinical problem whose consequences involve the endocrine, skeletal, and metabolic systems, as well as athletic functioning [1,2,7]. The current IOC consensus emphasizes that RED-S is no longer understood as a narrow syndrome affecting mainly women, but rather as a spectrum of consequences resulting from chronically reduced energy availability, affecting both sexes and various groups of sport disciplines [1]. In light of the available studies, the consequences related to bone health appear to be particularly well documented, whereas areas related to athletic performance, metabolic profile, and the clinical course in men remain more methodologically heterogeneous [1–3,17].

One of the most important conclusions emerging from the reviewed literature is that the strongest and most consistent evidence concerns bone health and the risk of bone stress injuries [2,13–17]. The meta-analysis by Gallant et al. indicated that the skeletal domain is the best clinically validated component of LEA and RED-S [2]. These findings are consistent both with

cross-sectional studies and with investigations using more advanced bone assessment techniques [14,17]. This means that high levels of physical activity alone do not always protect the skeleton if they are accompanied by chronic energy deficiency [15,17].

The high quality of data concerning bone health contrasts with the greater heterogeneity of findings related to athletic functioning [2,3,18–20]. Although the meta-analysis by Gallant et al. points to poorer running performance, impaired training response, reduced coordination and concentration, and greater training absence due to illness, the authors also emphasize the considerable heterogeneity of the included studies [2]. A similar conclusion follows from the review by Melin et al., in which it was noted that the effect of LEA on performance may be both direct and indirect, and that its presentation depends on the duration of energy deficiency, the type of sport, the athlete's training status, and the assessment tools used [3].

Hormonal and metabolic disturbances also represent an important area of consistency across studies, although here too the clinical picture appears more variable than in the case of bone health [1,7–12]. Original studies have consistently reported reductions in fT3, sex hormones, leptin, and IGF-1; however, their severity and practical diagnostic usefulness vary depending on the population studied, sex, the method used to assess LEA, and the duration of exposure [7–12]. This suggests that no single hormonal marker should be treated as a standalone diagnostic tool for RED-S [1,5,7].

One of the most important methodological problems present throughout much of the literature is the lack of a uniform standard for diagnosing LEA and RED-S [1,2,5,6]. Studies use different indicators, ranging from directly calculated energy availability, through RMR ratio, to screening tools such as the LEAF-Q or RED-S CAT2 [1,5,6]. This makes comparison of results across studies difficult and partly explains why the prevalence of LEA and RED-S differs so markedly between populations [1,2,22].

From the perspective of interpreting the findings, it is particularly important that RED-S is increasingly no longer regarded as a problem limited to women [1,7,25]. In recent years, a growing number of studies have focused on men; however, they still remain a minority compared with studies involving women [7,15,25]. One of the most important directions for future research should therefore be better characterization of the clinical picture of RED-S in men, including the diagnostic value of sex hormones, metabolic markers, and performance parameters [1,7,25].

When evaluating the quality of the available literature, several limitations should be noted. A substantial proportion of studies are cross-sectional in nature, which makes causal inference difficult [2,7]. Many studies are based on small sample sizes and on single-sex populations or populations limited to a single sport discipline [8–19]. The number of prospective studies with long-term follow-up remains limited, especially with regard to young athletes, men, and the effect of therapeutic interventions on the reversibility of changes [1,2,7,24,27,28]. These limitations should be taken into account when interpreting the findings and formulating practical conclusions.

10. Conclusions

Relative Energy Deficiency in Sport (RED-S) is a multisystem clinical problem resulting from problematic low energy availability that may affect both women and men participating in sport [1,7]. Analysis of the current literature indicates that its consequences primarily involve the endocrine, skeletal, and metabolic systems, as well as athletes' athletic functioning [1–3,7].

The best-documented consequences of RED-S concern bone health. Available studies confirm an association between chronic low energy availability and reduced bone mineral density, impaired bone microarchitecture, and an increased risk of bone stress injuries [2,13–17]. At the same time, RED-S is associated with hormonal and metabolic disturbances, including reductions in sex hormones, fT3, leptin, and other markers of adaptation to energy deficiency, reflecting the body's shift into an energy-conserving state [7–12].

The impact of RED-S on athletic functioning also appears to be significant, although the data in this area are more heterogeneous. Studies indicate an association between LEA and RED-S and impaired training response, reduced performance capacity, poorer concentration and coordination, and greater training absence due to illness or injury [2,3,10,18–20]. Groups at particularly high risk include endurance athletes, athletes in aesthetic and weight-category sports, young athletes, and individuals functioning under pressure related to body weight and body composition [1,21–26].

Early recognition of RED-S is crucial for reducing its health and performance-related consequences. In the absence of a single simple diagnostic test, a comprehensive approach is required, including assessment of symptoms, risk factors, dietary practices, training loads, and additional investigations [1,5,6]. The cornerstone of management remains correction of low energy availability through appropriately tailored nutritional intervention, modification of training loads, and, when necessary, interdisciplinary care [1,7,27]. Future research should

focus on standardizing methods for identifying LEA and RED-S, improving assessment in men and young athletes, and prospectively evaluating the effectiveness of clinical and educational interventions [1,2,5–7,24,27,28].

Disclosure

The authors report no disclosures.

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All authors have read and agreed with the published version of the manuscript.

Funding Statement:
This research received no external funding.

Institutional Review Board Statement:
Not applicable.

Informed Consent Statement:
Not applicable.

Data Availability Statement:
Not applicable.

Acknowledgments:
Not applicable.

Conflict of Interest Statement:
The authors declare no conflict of interest.

References

1. Mountjoy M, Ackerman KE, Bailey DM, et al. 2023 International Olympic Committee's (IOC) consensus statement on Relative Energy Deficiency in Sport (REDs). Br J Sports Med. 2023;57(17):1073-1097. doi:http://doi.org/10.1136/bjsports-2023-106994
2. Gallant TL, Ong LF, Wong L, et al. Low Energy Availability and Relative Energy Deficiency in Sport: A systematic review and meta-analysis. Sports Med. 2025;55(2):325-339. doi:http://doi.org/10.1007/s40279-024-02130-0
3. Melin AK, Areta JL, Heikura IA, Stellingwerff T, Torstveit MK, Hackney AC. Direct and indirect impact of low energy availability on sports performance. Scand J Med Sci Sports. 2024;34(1):e14327. doi:http://doi.org/10.1111/sms.14327
4. Burke LM, Ackerman KE, Heikura IA, et al. Mapping the complexities of Relative Energy Deficiency in Sport (REDs): Development of a physiological model by a subgroup of the International Olympic Committee (IOC) Consensus on REDs. Br J Sports Med. 2023;57(17):1098-1108. doi:http://doi.org/10.1136/bjsports-2023-107335
5. Stellingwerff T, Mountjoy M, McCluskey WT, et al. Review of the scientific rationale, development and validation of the International Olympic Committee Relative Energy Deficiency in Sport Clinical Assessment Tool: V.2 (IOC REDs CAT2). Br J Sports Med. 2023;57(17):1109-1118. doi:http://doi.org/10.1136/bjsports-2023-106914
6. International Olympic Committee Relative Energy Deficiency in Sport Clinical Assessment Tool 2 (IOC REDs CAT2). Br J Sports Med. 2023;57(17):1068-1072. doi:http://doi.org/10.1136/bjsports-2023-107549
7. Angelidi AM, Stefanakis K, Chou SH, et al. Relative Energy Deficiency in Sport (REDs): Endocrine manifestations, pathophysiology and treatments. Endocr Rev. 2024;45(5):676-708. doi:http://doi.org/10.1210/endrev/bnae011
8. Marzuki MIH, Jamil NA, Mohamad MI, et al. Energy availability and its association with health-related outcomes among national athletes at risk of relative energy deficiency in sports (REDs). BMJ Open Sport Exerc Med. 2024;10(4):e002193. doi:http://doi.org/10.1136/bmjsem-2024-002193
9. Moore EM, Drenowatz C, Williams BT, Brodrick TC, Stodden DF, Torres-McGehee TM. Male endurance athletes: Examination of energy and carbohydrate availability and hormone responses. Nutrients. 2024;16(21):3729. doi:http://doi.org/10.3390/nu16213729

10. Jurov I, Keay N, Spudić D, Rauter S. Inducing low energy availability in trained endurance male athletes results in poorer explosive power. Eur J Appl Physiol. 2022;122(2):503-513. doi:http://doi.org/10.1007/s00421-021-04857-4
11. McGuire A, Warrington G, Walsh A, Byrne T, Doyle L. Measurement of energy availability in highly trained male endurance athletes and examination of its associations with bone health and endocrine function. Eur J Nutr. 2024;63(7):2655-2665. doi:http://doi.org/10.1007/s00394-024-03433-8
12. Silvennoinen JIK, Sipilä PN, Valtonen M, et al. Association between the risk of relative energy deficiency in sport and cholesterol levels in Finnish endurance athletes. BMJ Open Sport Exerc Med. 2025;11(3):e002644. doi:http://doi.org/10.1136/bmjsem-2025-002644
13. Ikegami N, Samukawa M, Sakamaki-Sunaga M, et al. The influence of low energy availability on bone mineral density and trabecular bone microarchitecture of pubescent female athletes: A preliminary study. Int J Environ Res Public Health. 2022;19(9):5580. doi:http://doi.org/10.3390/ijerph19095580
14. Smith EM, Drager K, Groves EM, Gabel L, Boyd SK, Burt LA. New approach to identifying elite winter sport athletes' risk of relative energy deficiency in sport (REDs). BMJ Open Sport Exerc Med. 2025;11(1):e002320. doi:http://doi.org/10.1136/bmjsem-2024-002320
15. Haines MS, Kaur S, Scarff G, et al. Male runners with lower energy availability have impaired skeletal integrity compared to nonathletes. J Clin Endocrinol Metab. 2023;108(10):e1063-e1075. doi:http://doi.org/10.1210/clinem/dgad215
16. Holtzman B, Popp KL, Tenforde AS, Parziale AL, Taylor KM, Ackerman KE. Low energy availability surrogates associated with lower bone mineral density and bone stress injury site. PM R. 2022;14(5):587-596. doi:http://doi.org/10.1002/pmrj.12821
17. von Brackel FN, Munzinger R, Bartosik M, et al. Impact of Relative Energy Deficiency in Sport (REDs) on bone health in elite athletes: A retrospective analysis. J Cachexia Sarcopenia Muscle. 2025;16(5):e70082. doi:http://doi.org/10.1002/jcsm.70082
18. Lundstrom EA, Williams NI, Allaway HCM, et al. Pre-season energy deficiency predicts poorer performance during a competitive season in collegiate female long-distance runners. Eur J Sport Sci. 2025;25(3):e12261. doi:http://doi.org/10.1002/ejsc.12261
19. Stenqvist TB, Torstveit MK, Faber J, et al. Impact of a 4-week intensified endurance training intervention on markers of Relative Energy Deficiency in Sport (RED-S) and

performance among well-trained male cyclists. Front Endocrinol (Lausanne). 2020;11:512365. doi:http://doi.org/10.3389/fendo.2020.512365

20. Ackerman KE, Holtzman B, Cooper KM, et al. Low energy availability surrogates correlate with health and performance consequences of Relative Energy Deficiency in Sport. Br J Sports Med. 2019;53(10):628-633. doi:http://doi.org/10.1136/bjsports-2017-098958
21. Cabre HE, Moore SR, Smith-Ryan AE, Hackney AC. Relative Energy Deficiency in Sport (RED-S): Scientific, clinical, and practical implications for the female athlete. Dtsch Z Sportmed. 2022;73(7):225-234. doi:http://doi.org/10.5960/dzsm.2022.546
22. Marzuki MIH, Mohamad MI, Chai WJ, et al. Prevalence of Relative Energy Deficiency in Sport (RED-S) among national athletes in Malaysia. Nutrients. 2023;15(7):1697. doi:http://doi.org/10.3390/nu15071697
23. Lodge MT, Ward-Ritacco CL, Melanson KJ. Considerations of low carbohydrate availability (LCA) to Relative Energy Deficiency in Sport (RED-S) in female endurance athletes: A narrative review. Nutrients. 2023;15(20):4457. doi:http://doi.org/10.3390/nu15204457
24. Everett S. Optimizing performance nutrition for adolescent athletes: A review of dietary needs, risks, and practical strategies. Nutrients. 2025;17(17):2792. doi:http://doi.org/10.3390/nu17172792
25. Holtzman B, Kelly RK, Saville GH, et al. Low energy availability surrogates are associated with Relative Energy Deficiency in Sport outcomes in male athletes. Br J Sports Med. 2024;59(1):48-55. doi:http://doi.org/10.1136/bjsports-2024-109165
26. Vardardottir B, Gudmundsdottir SL, Tryggvadottir EA, Olafsdottir AS. Patterns of energy availability and carbohydrate intake differentiate between adaptable and problematic low energy availability in female athletes. Front Sports Act Living. 2024;6:1390558. doi:http://doi.org/10.3389/fspor.2024.1390558
27. Meyer A, Haigis D, Klos B, et al. Relative Energy Deficiency in Sport-Multidisciplinary Treatment in Clinical Practice. Nutrients. 2025;17(2):228. doi:http://doi.org/10.3390/nu17020228
28. DeJong Lempke AF, Reece LM, Whitney KE. Nutrition educational interventions for athletes related to low energy availability: A systematic review. PLoS One. 2025;20(2):e0314506. doi:http://doi.org/10.1371/journal.pone.0314506