BARTNIK, Katarzyna, WINKOWSKA, Alicja, POKRZEPA, Jakub Jan, BLECHARZ, Gabriela, SZWECH, Julia, JANKOWSKA, Marlena, HOSIAWA, Klara, SIEWIELEC, Aleksandra, MĘDRYSA, Karolina and CHLUBEK, Anna. The Evolution of Energy Deficiency Disorders in Female Athletes: Female Athlete Triad and Relative Energy Deficiency in Sport: Pathophysiology, Diagnosis, and Multidisciplinary Management - a literature review. Quality in Sport. 2025;42:60657. eISSN 2450-3118.
https://doi.org/10.12775/QS.2025.42.60657
https://apcz.umk.pl/QS/article/view/60657

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 Lp. 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: 30.04.2025. Revised: 10.06.2025. Accepted: 16.06.2025. Published: 17.06.2025.

The Evolution of Energy Deficiency Disorders in Female Athletes: Female Athlete Triad and Relative Energy Deficiency in Sport: Pathophysiology, Diagnosis, and Multidisciplinary Management - a literature review

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ABSTRACT

Introduction:

The growing participation of female athlethes in competitive and recreational sports has brought attention to sport-specific health concerns related to energy imbalance. The Female Athlete Triad (FAT), characterized by low energy availability (LEA), menstrual dysfunction and low bone mineral density (BMD), and the broader concept of Relative Energy Deficiency in Sport (RED-S) are critical syndromes affecting both health and performance.

Purpose:

The objective of this review is to examine the current literature on the etiology, pathophysiology, clinical presentation, diagnostic methods, management and prevention of FAT and RED-S in female athletes, with an emphasis on early recognition and interdisciplinary care.

Materials and methods:

This review is based on a comprehensive literature search conducted on articles sourced from PubMed and Cochrane. The listed keywords were used and analysed for topic relevance and knowledge currency.

Conclusion:

FAT and RED-S remain underdiagnosed despite significant health risks such as infertility, osteoporosis and reduced performance. Effective prevention and management depend on restoring energy balance that should be supported by a multidisciplinary care team. Continuation of research, education and monitoring are essential to minimize long-term consequences and promote a sport culture that prioritizes both performance and athlete well-being.

KEY WORDS:

Female Athlete Triad, Relative Energy Deficiency in Sport, Low Energy Availability, Menstrual Dysfunction, Bone Health, Stress Fractures, Energy Deficiency Syndromes, Female Athlete Health

INTRODUCTION:

The participation of females in competitive and recreational sports has grown recently.

It was partly caused by social, cultural, and institutional changes, such as the enactment of Title IX in the United States. This increase in athletic involvement has led to a greater awareness of sport-specific health concerns unique to the female population. One of the most significant and

well-documented of these is the Female Athlete Triad (FAT). FAT is traditionally characterized by three components: low energy availability (LEA) (with or without disordered eating), menstrual dysfunction, and low bone mineral density (BMD) [1].

More recently, to extend the FAT model, the International Olympic Committee (IOC) introduced the term Relative Energy Deficiency in Sport (RED-S) recognizing that LEA can have physiological consequences extending beyond reproductive and skeletal health [2].

RED-S includes a range of disorders in metabolic, endocrine, cardiovascular, gastrointestinal, hematological, and psychological functions. Research indicates that many cases of FAT and RED-S are still undiagnosed, especially in sports that emphasize leanness, endurance, or weight classes [3]. The aim of present review is to provide a comprehensive overview of the pathophysiology clinical presentation, and current strategies for the identification and management of FAT and RED-S among female athletes.

DEFINITION AND CONCEPTUAL EVOLUTION

The Female Athlete Triad (FAT) is a medical syndrome originally defined by the American College of Sports Medicine (ACSM) in 1992 as the coexistence of disordered eating, amenorrhea, and osteoporosis in physically active females [1]. This narrow definition was found to exclude many athletes who presented only one or two components or subclinical symptoms. However, the definition has evolved in 2007 when ACSM revised the model, redefining FAT as a spectrum disorder composed of **low energy availability (LEA) (with or without disordered eating), menstrual dysfunction, and low bone mineral density (BMD).** The latest change allows for the diagnosis of the triad even if only one or two components are present [2]. Moreover, in 2014 the International Olympic Committee (IOC) introduced the term of **Relative Energy Deficiency in Sport (RED-S)** [3]. RED-S describes a set of health and performance impairments, including effects on metabolic, cardiovascular, immune, psychological, and endocrine systems, and applies to both female and male athletes.

Unlike FAT, RED-S provides a more inclusive and clinically practical framework, pointing LEA as the primary cause of systemic dysfunction in athletes [4].

ETIOLOGY AND PATHOPHYSIOLOGY

Etiology

The etiology of the Female Athlete Triad (FAT) and Relative Energy Deficiency in Sport (RED-S) is multifactorial. It involves behavioral, psychological, environmental, and physiological interactions. Low energy availability is the main element of the triad. It occurs when dietary

energy intake is insufficient to support both exercise demands and normal physiological functions[5], [6]. This energy deficiency may result from intentional caloric restriction, unintentional undernutrition, or a combination of excessive energy consumption and inadequate intake [7]. Psychological and sociocultural factors, including body image dissatisfaction, perfectionism, fear of weight gain, and pressure from coaches or peers, also play a critical role in developing disordered eating behaviors and LEA [2], [8]. High-risk populations include athletes participating in aesthetic, endurance, and weight-category sports, where leanness is often associated with performance and success [4], [5]. These behaviors are influenced by training intensity, early sport specialization, and hormonal changes during adolescence, which may increase vulnerability to energy deficits and related dysfunctions [9].

Pathophysiology

The pathophysiology of the Female Athlete Triad (FAT) and its expanded model, Relative Energy Deficiency in Sport (RED-S), is centrally driven by low energy availability (LEA), which initiates a cascade of metabolic, endocrine, and skeletal dysfunctions. These impairments are not isolated; rather, they interact across systems, resulting in clinical consequences such as menstrual disturbances and decreased bone mineral density (BMD). The RED-S framework underscores that the effects of LEA extend well beyond the triadic scope, affecting multiple physiological domains [10].

Low Energy Availability (LEA)

LEA occurs when dietary energy intake is insufficient to support both exercise expenditure and the energy required for basic physiological functions [2].

It may arise from disordered eating, compulsive behaviors, or unintentional under-fueling, especially among athletes in leanness-focused sports [8]. The hypothalamus responds to energy deficiency by downregulating key metabolic and reproductive axes. Hormonal alterations include reductions in leptin, insulin, and triiodothyronine (T3), alongside increases in cortisol, representing an endocrine profile indicative of energy conservation [10], [11].

While LEA is central to both FAT and RED-S, its identification remains challenging. Direct assessment of energy availability is complex and resource-intensive, requiring accurate measurements of dietary intake, energy expenditure, and fat-free mass. Consequently, indirect tools such as questionnaires are often employed for screening, albeit with limitations in sensitivity and specificity [2].

Menstrual Dysfunction

One of the main consequences of LEA in female athletes is functional hypothalamic amenorrhea (FHA). Suppressed pulsatile secretion of gonadotropin-releasing hormone (GnRH)

leads to diminished luteinizing hormone (LH) and follicle-stimulating hormone (FSH) output, resulting in hypoestrogenism and menstrual irregularity [10], [11]. The spectrum of menstrual dysfunction includes luteal phase defects, oligomenorrhea, and secondary amenorrhea, each reflecting varying degrees of hypothalamic suppression. The presence of menstrual dysfunction signals significant disruption of neuroendocrine regulation Impaired bone turnover, cardiovascular strain, and altered lipid profiles are also the cosequences [11].

Low Bone Mineral Density (BMD)

LEA and hypoestrogenism synergistically reduce bone mineral density, increasing the risk of osteopenia, osteoporosis, and stress fractures. Estrogen plays a key role in bone homeostasis by inhibiting osteoclast activity and promoting osteoblastic bone formation. Its deficiency disrupts the balance of bone remodeling, favoring resorption and net bone loss [10], [12].

In athletic populations, BMD deficits are particularly concerning during adolescence, when peak bone mass is being established. Inadequate energy and nutrient intake during this critical period can result in irreversible reductions in skeletal strength. Clinical manifestations include increased susceptibility to bone stress injuries (BSIs) and stress fractures, most commonly affecting the tibia and metatarsals in female athletes [12], [13]. Stress fractures, representing 10–20% of all sports injuries, are frequently observed in females due to the cumulative effects of LEA, menstrual dysfunction, and compromised skeletal loading [12]. Female sex, low BMI, and older age at menarche have been identified as risk factors for stress fractures among athletes [13].

CLINICAL MANIFESTATIONS

The clinical spectrum of the Female Athlete Triad (FAT) and Relative Energy Deficiency in Sport (RED-S) is observed as a wide range of physiological disorders that are the consequences of chronic low energy availability (LEA). These manifestations may appear subtly and vary across individuals, often avoiding early diagnosis, because such symptoms may be normalized or attributed to high training demands [2].

Reproductive and Endocrine Systems

Reproductive dysfunction is one of the earliest and most recognized signs of LEA in female athletes. LEA disrupts the hypothalamic-pituitary-gonadal (HPG) axis, suppressing gonadotropin-releasing hormone (GnRH) pulsatility, which leads to reduced luteinizing hormone (LH) and follicle-stimulating hormone (FSH) secretion and ultimately to hypoestrogenism [11]. This hormonal disturbance manifests clinically as functional

hypothalamic amenorrhea (FHA), as well as oligomenorrhea or luteal phase defects [2]. Additionally, RED-S is associated with systemic endocrine adaptations, including decreased levels of triiodothyronine (T3), leptin, and insulin, and elevated cortisol levels, indicating a catabolic hormonal profile designed to conserve energy [10]. These endocrine abnormalities not only imfluence menstrual function but also contribute to impaired metabolic rate, decreased growth and repair, and increased psychological stress response [11].

Skeletal System and Bone Health

Impairment in bone health is a clinical manifestation of both FAT and RED-S. Poor nutrient intake with estrogen deficiency and suppressed insulin-like growth factor-1 (IGF-1) disrupts bone remodeling by increasing osteoclastic activity and reducing osteoblastic bone formation [12]. The result is decreased bone mineral density (BMD), predisposing to osteopenia, osteoporosis, and stress fractures, particularly during adolescence when peak bone mass is being established [2]. Epidemiological studies show that stress fractures are disproportionately common in female athletes, especially in sports involving high impact or leanness emphasis. Weight-bearing bones such as the tibia, femur, and metatarsals are most frequently affected [13]. Stress fractures in this population often lead to sport withdrawal and prolonged recovery periods, further exacerbating physical and psychological strain [12].

Metabolic, Cardiovascular, and Immune Function

Chronic LEA in RED-S affects basal metabolism, often leading to reduced resting metabolic rate, fatigue, cold intolerance, and impaired recovery from training [11]. In the cardiovascular system, hypoestrogenism contributes to endothelial dysfunction, abnormal lipid profiles, and potential long-term cardiovascular risk, particularly if energy deficiency occurs during dolescence [2]. Immunological disturbances as increased susceptibility to illness and infection have also been observed. They result from suppressed immune function due to hormonal changes and micronutrient deficiencies [10].

Psychological and Behavioral Health

Psychological manifestations are integral components of RED-S and often both a cause and consequence of LEA. Athletes frequently suffer from mood disturbances, depression, anxiety, and obsessive exercise behavior [8].

SCREENING AND DIAGNOSIS

Effective screening and early diagnosis of the Female Athlete Triad (FAT) and Relative Energy Deficiency in Sport (RED-S) are essential to prevent long-term physiological damage and promote safe athletic participation. Diagnosis requires a multidimensional approach, including clinical history, structured screening tools, and objective physiological assessments [2].

Clinical Assessment and History

Initial evaluation should include a detailed history of menstrual function, training load, dietary behaviors, stress fractures, and psychological stress. Adolescents are particularly vulnerable due to their ongoing development and heightened energy demands. Atypical signs—such as menstrual irregularity, fatigue, and frequent injury—may be mistaken as "normal" in athletic contexts, delaying intervention [4]. Risk is particulary elevated in athletes participating in endurance, aesthetic, or weight-class sports [6]. Despite its significance, evidence suggests that many primary care providers and athletic staff remain still not informed enough about FAT and RED-S. That leads to low screening rates and inconsistent interventions. [3].

Screening Tools and Questionnaires

Due to the complexity of directly measuring energy availability, several screening questionnaires have been developed and validated. The LEAF-Q (Low Energy Availability in Females Questionnaire), RED-S Screening Tool (RST), and SEAQ-I are commonly used to assess clinical symptoms and behaviors associated with LEA and RED-S [10].

Although these instruments are accessible and cost-effective, they depend on self-report.

In populations with low symptom awareness or performance-related denial they are susceptible to response bias. A recent review emphasizes that screening tools are useful but insufficient alone, and must be combined with clinical judgment and physiological data [14].

Objective Measures and Biomarkers

Objective diagnostics play a significant role in confirming RED-S or FAT. Dual-energy X-ray absorptiometry (DXA) is the gold standard for evaluating bone mineral density (BMD) and is indicated in athletes with amenorrhea or recurrent stress fractures [4], [6].

Laboratory assessment of estradiol, FSH, LH, T3, cortisol, and leptin levels provides hormonal evidence of hypothalamic suppression, metabolic downregulation, or chronic stress [2]. However, defining diagnostic criteria for RED-S remains challenging. Current methods are criticized for relying too much on symptoms and causing difficulties with distinguishing

between normal physiological adaptations and pathological conditions. This highlights the need for standardized, evidence-based diagnostic guidelines [15].

MANAGEMENT AND TREATMENT

The effective treatment of the Female Athlete Triad (FAT) and Relative Energy Deficiency in Sport (RED-S) requires a multidisciplinary, evidence-based approach that targets the primary cause: low energy availability (LEA). Managing physiological disabilities in bone health, menstrual function, and metabolism demands coordinated efforts from medical, nutritional, and psychological professionals [16].

Nutritional Rehabilitation and Energy Availability

Restoring energy availability is the basis of treatment. Increases in dietary energy intake and reductions in exercise load are necessary to change a catabolic to an anabolic state.

Dietary interventions should prioritize macronutrient balance, with special attention to carbohydrates for hormonal restoration and protein for muscle and bone recovery. Additionally, adequate intake of micronutrients—including calcium, vitamin D, iron, and zinc—is essential to support endocrine and skeletal repair [17]. Energy availability above 45 kcal/kg fat-free mass/day is generally recommended to support resumption of menstrual cycles and metabolic normalization [18].

Hormonal and Endocrine Recovery

LEA suppresses critical axes regulating reproduction, thyroid function, and metabolism.

It leads to reductions in estradiol, luteinizing hormone (LH), insulin-like growth factor-1 (IGF-1), and T3, alongside elevated cortisol levels. These changes affects menstrual function, increase bone resorption, and delay tissue recovery [18]. Hormonal therapies, such as oral contraceptives, should not be used as first-line interventions. They induce withdrawal bleeding and may mask the return of natural ovulatory cycles [16].

Multidisciplinary Support and Clinical Awareness

Successful management depends on a coordinated interdisciplinary team, including sports physicians, psychologists, dietitians, and physical therapists. Education for both athletes and healthcare providers is crucial. A recent survey revealed that many clinicians still lack knowledge of RED-S criteria, incorrectly associate diagnosis with low BMI alone, and may over-rely on hormonal contraceptives for amenorrhea management [16]. Furthermore, collaboration between the medical team and coaches is essential to support behavior change and reduce training loads when indicated [5].

Bone Health and Injury Prevention

Improvement of bone health requires appropriate nutritional intake, adjustments of movement and careful monitoring. Dual-energy X-ray absorptiometry (DXA) should be used to assess bone mineral density (BMD), particularly in athletes with amenorrhea or prior stress fractures [11]. If LEA and amenorrhea persist, the athlete may fail to reach peak bone mass, increasing lifelong fracture risk. Calcium (1,300–1,500 mg/day) and vitamin D (1,000–2,000 IU/day) supplementation, as well as weight-bearing exercise djusted to the current recovery phase are recommended [11].

Emerging Perspectives and Metabolic Research

Metabolic research associates RED-S and FAT with disruptions in lipid, amino acid, and glucose metabolic pathways, which may help explain the multisystem effects observed in affected female athletes. Advanced techniques, such as Mendelian randomization, are being explored to clarify relationships between specific metabolic profiles and reproductive dysfunction, potentially offering future therapeutic targets [19].

PREVENTION AND EDUCATION

Raising Awareness and Risk Identification

Awareness of FAT and RED-S remains insufficient among healthcare professionals, coaches, and athletes. Multiple studies have shown that many are unable to correctly identify the three components of the Triad or understand the mechanisms behind RED-S [16]. Prevention should include education on the risks of low energy availability (LEA), with emphasis on how menstrual irregularity and recurrent injury may signal deeper physiological disruption. Routine screening—particularly among high-risk athletes in lean sports—is vital for early detection [20].

Athlete and Coach Education

Athlete education is fundamental to prevent LEA and its consequences. Instruction on nutritional intake, energy balance, and healthy training practices must be integrated into regular coaching and medical support structures. Coaches, especially in sports emphasizing leanness or aesthetics, should receive specific training to help to cultivate a performance culture that values health as well as athletic results. Additionally, educational interventions should focus on recognizing early signs of RED-S, including changes in mood, sleep quality, menstrual cycle regularity, and recovery patterns. Preventive education also includes providing clear return-to-play protocols and encouraging athletes to report irregularities without stigma [17].

Integrating Menstrual Monitoring in Prevention

Menstrual health tracking has arisen as a practical and non-invasive tool for monitoring energy status in female athletes. Changes such as luteal phase defects, anovulation, or amenorrhea often occur before overall performance starts to get worse and can signal hormonal and energy imbalance. Education on how to use menstrual indicators to monitor training response and readiness can empower athletes to take an active role in their own physiological management. Furthermore, menstrual dysfunction should no longer be seen as an isolated issue, because it is recognized as an early sign for broader endocrine disruption that can impair cardiovascular, immune, and neuromuscular performance pathways [21].

CONCLUSION

The Female Athlete Triad (FAT) and Relative Energy Deficiency in Sport (RED-S) are energy deficiency syndromes with broad health and performance consequences. While FAT focuses on menstrual dysfunction, bone health, and low energy availability, RED-S involves additional physiological domains, including metabolism, immunity, and psychological function. Timely recognition and intervention are essential to prevent irreversible outcomes, such as osteoporosis, infertility, and performance deterioration. Management should prioritize the restoration of energy availability, supported by nutritional strategies, training modifications, and psychological care, rather than symptom-masking pharmacological approaches.

Long-term prevention requires systematic education, routine screening and enhanced awareness among athletes, coaches, and healthcare professionals, favoring a sport environment that upholds both athletic performance and long-term health.

Disclosure:

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All authors have reviewed and agreed to the publication of the final version of the manuscript.

Conflict of Interest Statement:

The authors declare no conflicts of interest.

Funding Statement:

This study did not receive any special funding.

Informed Consent Statement:

Not applicable.

Institutional Review Board Statement:

Not applicable.

Data availability Statement:

Not applicable.

Acknowledgments:

Not applicable.

Ethics Committee Statement:

Not applicable.

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