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## IMPACT OF LOW ENERGY AVAILABILITY ON HORMONAL PROFILES AND ATHLETIC PERFORMANCE

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**Abstract**

***Background:*** Low energy availability in athletes impacts hormonal regulation, especially in females. Insufficient caloric intake affects the hypothalamic-pituitary-gonadal axis, causing decreased pulsatile release of hormones and a reduction in estradiol production, leading to functional hypothalamic amenorrhea.

***Aim of study:*** This study aims to explore the specific impacts of low energy availability on hormonal profiles and athletic performance, focusing on the relationship between estradiol levels and performance outcomes in female athletes.

***Methods:*** A literature review examined the impact of LEA on hormonal profiles and athletic performance, focusing on Albanian female athletes and cultural and nutritional factors.

***Results:*** The findings indicate that lower estradiol levels negatively impact mitochondrial function, leading to decreased endurance performance and prolonged recovery periods. Chronic energy shortages increase cortisol levels, impacting menstrual cycles and increasing musculoskeletal injuries. Monitoring hormonal profiles is crucial for early detection and prevention.

***Discussion:*** The study highlights the significant impact of Leukemia-associated autoimmune disease (LEA) on hormonal profiles and athletic performance in female athletes, emphasizing the importance of estradiol balance for optimal health outcomes.

***Conclusion:*** Estradiol regulates body composition, energy use, and performance in female athletes, especially under low energy availability. Addressing sociocultural factors requires culturally appropriate methods, psychological support, and nutritional education. Future initiatives should integrate multidisciplinary support networks.

**Keywords:** *Low Energy Availability (LEA), Estradiol, Hormonal Regulation, Athletic Performance, Cortisol, Female Athletes*

## Introduction

Low Energy Availability (LEA) has emerged as a central concern in sports medicine and performance physiology, particularly among female athletes. LEA occurs when dietary energy intake fails to adequately meet the combined demands of exercise and essential physiological functions (Mountjoy, M., Sundgot-Borgen, J.K., Burke, L.M., Ackerman, K.E., Blauwet, C., Constantini, N., Lebrun, C., Lundy, B., Melin, A.K., Meyer, N. L., Sherman, R.T., Tenforde, A.S., Klungland Torstveit, M., & Budgett, R., 2018). Low energy availability (LEA) arises when an athlete's caloric intake is inadequate to satisfy both the physical demands of their training and essential physiological processes. The resulting energy deficit disrupts the hypothalamic-pituitary-gonadal (HPG) axis, reducing gonadotropin-releasing hormone (GnRH) secretion and impairing estrogen production, primarily estradiol (De Souza, M.J., Nattiv, A., Joy, E., Misra, M., Williams, N.I., Mallinson, R.J., Gibbs, J.C., Olmsted, M., Goolsby, M., Matheson, G., & Expert Panel, 2014; Melin, A., Tornberg, Å.B., Skouby, S., Møller, S.S., Sundgot-Borgen, J., Faber, J., Sidelmann, J.J., Aziz, M., & Sjödin, A., 2015). Emerging research has highlighted that LEA is not only a condition of insufficient energy but also a critical stressor that disrupts multiple hormonal pathways, leading to wide-ranging physiological consequences (Mountjoy, M., Sundgot-Borgen, J.K., Burke, L.M., Ackerman, K.E., Blauwet, C., Constantini, N., Lebrun, C., Lundy, B., Melin,A.K., Meyer, N.L., Sherman, R.T., Tenforde, A.S., Klungland Torstveit, M., & Budgett, R., 2018). This imbalance in energy can significantly impact hormonal regulation, especially in female athletes, as the hypothalamic-pituitary-gonadal (HPG) axis is particularly responsive to changes in energy levels. LEA leads to a decrease in the pulsatile release of gonadotropin-releasing hormone (GnRH), which subsequently reduces the secretion of luteinizing hormone (LH) and follicle-stimulating hormone (FSH). This sequence of hormonal changes results in lower estradiol production, a critical feature of functional hypothalamic amenorrhea (FHA) (Cabre, H.E., Moore, S.R., Smith-Ryan, A.E., & Hackney, A.C., 2022). Moreover, this hormonal disturbance contributes to a cascade of health problems including functional hypothalamic amenorrhea (FHA), compromised bone mineral density, and reduced athletic performance.

Recent evidence also implicates LEA in altering thyroid function (low T3) and elevating stress hormone levels, particularly cortisol (Ackerman K. E., Holtzman B., Cooper K. M., et al., 2019; Slater, J., Brown, R., McLay-Cooke, R., & Black, K., 2017). These adaptations, while potentially protective in the short term, have deleterious long-term consequences on recovery, immunity, and performance. Furthermore, female athletes in developing nations such as Albania may be at increased risk due to sociocultural pressures, insufficient sports nutrition education, and limited access to health monitoring (Caushi Alketa and Latollari, Elda and Cuka, Agron, 2022; Wasserfurth, P., Palmowski, J., Hahn, A., & Krüger, K., 2020).

While previous discussions have addressed estradiol's role in preventing Relative Energy Deficiency in Sport (RED-S), this section examines the specific ways in which LEA interferes with estradiol production. The suppression of estradiol not only impacts reproductive health but also influences other endocrine systems, including the thyroid and adrenal glands. A recent study has showed that athletes experiencing LEA often show decreased levels of triiodothyronine (T3) and increased cortisol, which can lead to compromised metabolic function and a higher risk of injuries (Castanier, C., Bougault, V., Teulier, C., Jaffré, C., Schiano-Lomoriello, S., Vibarel-Rebot, N., Villemain, A., Rieth, N., Le-Scanff, C., Buisson, C., & Collomp, K., 2021). This article aims to provide an updated, multidisciplinary view on the physiological consequences of LEA, especially its impact on estradiol and related hormonal profiles, while addressing performance outcomes in elite female athletes. Cultural context is considered vital, as body image norms and dietary restrictions can influence energy balance and endocrine health (Logue, D.M., Madigan, S.M.,

Melin, A., Delahunt, E., Heinen, M., Donnell, S.M., & Corish, C.A., 2020). This study aims to explore the specific impacts of low energy availability on hormonal profiles and athletic performance, focusing on the relationship between estradiol levels and performance outcomes in female athletes.

## Methodology

This study employs a comprehensive literature review, analyzing existing research on the effects of LEA on hormonal profiles and athletic performance, particularly focusing on female athletes. In this review, over 60 articles were systematically evaluated using predefined inclusion and exclusion criteria related to female athletic populations and LEA-induced hormonal dysregulation. Key databases were consulted to identify peer-reviewed articles that explore hormonal changes associated with LEA, the physiological implications for athletic performance, and strategies for monitoring and intervention. Grey literature, including expert consensus statements and guidelines from sports federations, was also incorporated to align clinical perspectives with research evidence. Studies were evaluated based on quality criteria, including clarity of methodology, participant selection, and hormonal outcome measures. Both cross-sectional and longitudinal designs were reviewed to compare short- and long-term effects of LEA. This study is based on a narrative and integrative literature review that examined scholarly research published between 2010 and 2024 concerning the physiological, hormonal, and performance effects of low energy availability (LEA) in female athletes. Databases such as PubMed, ScienceDirect, Scopus, and Google Scholar were used to identify relevant peer-reviewed articles. Keywords included 'low energy availability', 'estradiol suppression', 'functional hypothalamic amenorrhea', 'female athlete triad', 'RED-S', and 'performance outcomes in female athletes'. Studies were selected based on empirical design quality, relevance to endurance and strength athletes, and inclusion of hormonal biomarkers such as estradiol, cortisol, T3, and LH (Melin, A., Tornberg, Å.B., Skouby, S., Møller, S.S., Sundgot-Borgen, J., Faber, J., Sidelmann, J.J., Aziz, M., & Sjödin, A., 2015). Inclusion criteria consisted of studies written in English, focused on human female athletes, and providing empirical or review-based analysis of hormonal changes in response to LEA. Research including athletes from culturally comparable populations to Albania was prioritized. Articles addressing both physiological mechanisms and applied outcomes (e.g., endurance, strength, menstruation, recovery) were included.

A subset of data concerning Albanian female athletes was drawn from national surveys, sports university records, and studies published in regional journals (Caushi Alketa and Latollari, Elda and Cuka, Agron, 2022). Additionally, reports from international sports medicine organizations were referenced to contextualize health guidelines and best practices (Mountjoy M., Sundgot-Borgen J., Burke L., et al., 2014; WADA. 2022). The review also incorporates findings specific to Albanian female athletes, considering cultural and nutritional factors.

## Results

1. **Estradiol and Athletic Performance under LEA:** Lowered levels of estradiol negatively affect mitochondrial function, which is essential for energy generation during endurance activities. Research indicates that estradiol improves mitochondrial efficiency by influencing oxidative phosphorylation and decreasing the production of reactive oxygen species (ROS) (Cabre, H.E., Moore, S.R., Smith-Ryan, A.E., & Hackney, A.C., 2022). In elite Albanian athletes, where cultural dietary habits may intensify energy shortages, the reduction of estradiol can result in decreased endurance performance, lower force generation, and prolonged recovery periods. Estradiol, essential for lipid metabolism and glycogen preservation, is linked to impaired mitochondrial function in female athletes, causing decreased aerobic capacity and delayed recovery due to LEA (Ihalainen, J.K., Mikkonen, R.S., Ackerman, K.E. et al., 2024; Enns, D.L., & Tiidus, P.M., 2010).
2. **Interaction between Estradiol and Cortisol:** Increased cortisol levels, which often occur due to chronic

energy shortages, further suppress estradiol by diminishing the pulsatility of GnR H. This disruption in hormonal balance affects menstrual cycles and heightens the likelihood of musculoskeletal injuries due to bone resorption prompted by cortisol (Cabre, H. E., Moore, S. R., Smith-Ryan, A. E., & Hackney, A. C., 2022). The combined effects of estradiol and cortisol on athletic performance can lead to reduced lean body mass, a crucial factor in performance outcomes, particularly harmful for female athletes in Albania who participate in strength-oriented sports (Castanier, C., Bougault, V., Teulier, C., Jaffré, C., Schiano-Lomoriello, S., Vibarel-Rebot, N., Villemain, A., Rieth, N., Le-Scanff, C., Buisson, C., & Collomp, K., 2021). Studies show that elevated cortisol levels due to LEA further suppress GnRH and inhibit estradiol production, creating a vicious cycle of hormonal disruption (De Souza, M. J., Nattiv, A., Joy, E., Misra, M., Williams, N. I., Mallinson, R. J., Gibbs, J. C., Olmsted, M., Goolsby, M., Matheson, G., & Expert Panel, 2014; Cabre, H. E., Moore, S. R., Smith-Ryan, A. E., & Hackney, A. C., 2022). This imbalance contributes to menstrual dysfunction, decreased bone density, and increased risk of musculoskeletal injuries (Melin, A., Tornberg, Å. B., Skouby, S., Møller, S. S., Sundgot-Borgen, J., Faber, J., Sidelmann, J. J., Aziz, M., & Sjödin, A., 2015; Tenforde, A. S., Barrack, M. T., Nattiv, A., & Fredericson, M., 2016).

3. **Cardiovascular Health Implications:** Estradiol promotes vasodilation by influencing endothelial nitric oxide synthase (eNOS). Reduced endothelial function caused by low estradiol levels in LEA results in less blood flow and oxygen supply to active muscles. Increased arterial stiffness and a higher risk of cardiovascular disease have been associated with this vascular dysfunction in female athletes suffering from long-term energy deficits (Cabre, H. E., Moore, S. R., Smith-Ryan, A. E., & Hackney, A. C., 2022). Estradiol deficiency, induced by LEA, can lead to cardiovascular impairments, including arterial stiffness, increased heart rate, and reduced oxygen delivery, potentially increasing cardiovascular risk in high-performing athletes (Elliott-Sale, K. J., Minahan, C. L., de Jonge, X. A. K. J., Ackerman, K. E., Sipilä, S., Constantini, N. W., Lebrun, C. M., & Hackney, A. C., 2021). Early identification of vascular dysfunction is crucial for Albanian athletes, who may have restricted access to sophisticated medical monitoring.
4. **Longitudinal Monitoring of Hormonal Profiles:** Establishing a hormone monitoring program for Albanian female athletes may aid in spotting LEA early and averting long-term health issues. Regular measurement of estradiol, cortisol, and T3 levels can provide important information about an athlete's energy balance and overall health, aligning with the World Anti-Doping Agency's recommendations for monitoring hormonal changes (Collomp K., 2022). Hormonal monitoring, including estradiol, cortisol, and T3 levels, was found to be a reliable method to detect early signs of energy deficiency and performance degradation. Several studies recommend implementing hormonal tracking in sports programs for adolescent and elite-level athletes (Logue, D. M., Madigan, S. M., Melin, A., Delahunt, E., Heinen, M., Donnell, S. M., & Corish, C. A., 2020; WADA. 2022).
5. **Nutritional Strategies:** A multidisciplinary approach is necessary to address LEA, with nutrition playing a crucial role in reestablishing hormonal balance. An adequate diet of macronutrients – particularly fats and carbohydrates – is essential for maintaining estradiol synthesis and overall endocrine function. Incorporating traditional Albanian foods high in healthy fats can enhance energy availability and promote estradiol production. In Albanian female ath-

letes, dietary practices low in fat and carbohydrates have been associated with menstrual disturbances, early fatigue, and immune suppression (Caushi Alketa and Latollari, Elda and Cuka, Agron, (2022). Moreover, insufficient access to medical screenings and sports psychology services contributes to under diagnosis and poor intervention.

6. **Psychological and Social Factors:** The psychological and social elements contributing to energy shortages are often overlooked. Chronic calorie restriction and disordered eating patterns may arise from the rigorous training demands of professional sports and cultural pressures (Wasserfurth, P., Palmowski, J., Hahn, A., & Krüger, K., 2020). Psychological disturbances such as increased anxiety, poor body image, and reduced concentration are frequently reported among athletes with LEA, correlating with hormonal imbalances and overtraining syndrome (Slater, J., Brown, R., McLay-Cooke, R., & Black, K., 2017; Gibbs, J.C., Williams, N.I., & De Souza, M.J., 2013). These challenges can be exacerbated for Albanian female athletes due to limited access to mental health and sports nutrition specialists.

The findings indicate that lower estradiol levels negatively affect mitochondrial function, which is critical for energy generation during endurance activities. Estradiol is shown to enhance mitochondrial efficiency, and its reduction can lead to decreased endurance performance, lower force generation, and prolonged recovery periods, especially in athletes with high aerobic demands (Ihalainen, J.K., Mikkonen, R.S., Ackerman, K.E. et al., 2024). LEA, along with other factors, can lead to maladaptive changes, impairing physiological systems and affecting health, well-being, and sport performance, resulting in REDs, including neuroendocrine, bone, immune, and hematological effects (Angelidi, A.M., Stefanakis, K., Chou, S.H., Valenzuela-Vallejo, L., Dipla, K., Boutari, C., Ntoskas, K., Tokmakidis, P., Kokkinos, A., Goulis, D. G., Papadaki, H.A., & Mantzoros, C.S., 2024). There is also evidence that suppressed estradiol may impair neuromuscular coordination, thus increasing the risk of injury during high-intensity movements and competition (Gibbs, J.C., Williams, N.I., & De Souza, M.J., 2013). Additionally, increased cortisol levels due to chronic energy shortages further suppress estradiol, impacting menstrual cycles and increasing the risk of musculoskeletal injuries (Cabre, H.E., Moore, S.R., Smith-Ryan, A.E., & Hackney, A.C., 2022). The study also highlights the importance of monitoring hormonal profiles to detect LEA early and prevent long-term health issues.

## Discussion

The findings underscore the significant impact of LEA on hormonal profiles and athletic performance in female athletes. Estradiol's role in maintaining energy balance, muscle mass, and cardiovascular health is critical, particularly in the context of LEA. Estradiol is also crucial for bone health, menstrual function, and hunger regulation-all of which are necessary for sustaining long-term health and athletic performance. Cumulative evidence underscores the central role of estradiol in athletic performance and long-term health outcomes. Estradiol's regulation of energy metabolism, muscle repair, bone integrity, and cardiovascular efficiency is particularly critical for female athletes operating under the chronic stress of high training loads and restricted energy availability (De Souza, M.J., Nattiv, A., Joy, E., Misra, M., Williams, N.I., Mallinson, R.J., Gibbs, J.C., Olmsted, M., Goolsby, M., Matheson, G., & Expert Panel, 2014; Ihalainen, J.K., Mikkonen, R.S., Ackerman, K.E. et al., 2024).

Recent evidence suggests that interventions targeting menstrual tracking and education among athletes and coaches may significantly reduce the incidence of RED-S (Hunter, N.N., & Smith, M.A., 2024). The chronic under diagnosis of LEA among adolescent athletes raises concerns regarding long-term hormonal programming and reproductive capacity in later life (Ackerman K.E., Holtzman B., Cooper K.M., et al., 2019). A coordinated care model that includes nutritionists, psychologists, and endocrinologists is essential to support athletes through recovery from LEA and

to prevent recurrence (Holtzman, B., & Ackerman, K.E., 2021). Implementing energy availability screening protocols during pre-season evaluations could serve as an early warning system for physiological stress and hormonal imbalance (Tenforde, A.S., Barrack, M.T., Nattiv, A., & Fredericson, M., 2016). It is now widely recognized that energy availability is a more precise marker of athlete health than body weight or BMI alone. Subclinical hormonal disruptions can occur even in athletes who appear physically fit and lean (Mountjoy, M., Sundgot-Borgen, J.K., Burke, L.M., Ackerman, K.E., Blauwet, C., Constantini, N., Lebrun, C., Lundy, B., Melin, A. K., Meyer, N.L., Sherman, R.T., Tenforde, A.S., Klungland Torstveit, M., & Budgett, R., 2018). In addition to reproductive suppression, LEA has been associated with impaired immune function and altered neuromuscular coordination, which may increase the risk of overuse injuries and illness in endurance athletes (Slater, J., Brown, R., McLay-Cooke, R., & Black, K., 2017; Gibbs, J.C., Williams, N.I., & De Souza, M.J., 2013).

However, by interfering with the hypothalamic-pituitary-gonadal (HPG) axis, LEA interferes with the synthesis of estradiol, which results in menstrual irregularities, decreased bone mineral density (BMD), and a decreased ability for endurance and recuperation.

LEA-induced endocrine disruptions extend beyond estradiol. Low T3 levels reflect thyroid suppression, whereas high cortisol indicates chronic stress – both of which are linked to decreased performance, mood instability, and increased susceptibility to illness and overtraining (Mountjoy M., Sundgot-Borgen J., Burke L., et al., 2014; Elliott-Sale, K.J., Minahan, C.L., de Jonge, X.A.K.J., Ackerman, K.E., Sipilä, S., Constantini, N.W., Lebrun, C. M., & Hackney, A. C., 2021). The hormonal instability significantly affects psychological well-being, a factor that must be addressed through athlete-centered care. Integrating multidisciplinary interventions – such as nutritional counseling, mental health support, and regular hormonal screenings – has been shown to improve both health markers and performance outcomes (Ackerman K.E., Holtzman B., Cooper K.M., et al., 2019; Logue, D.M., Madigan, S.M., Melin, A., Delahunt, E., Heinen, M., Donnell, S.M., & Corish, C.A., 2020). Digital health tools and mobile applications offer promising avenues for tracking symptoms, menstrual cycles, and performance metrics in real time (Holtzman, B., & Ackerman, K.E., 2021). Advancements in mobile health monitoring – such as wearable devices that track heart rate variability, sleep quality, and caloric expenditure – offer new opportunities for early detection and individualized LEA interventions (Hunter, N.N., & Smith, M.A., 2024). Another dimension worth addressing is the role of energy periodization and intra-cycle energy deficits, where athletes maintain adequate overall intake but fail to match energy availability during intense training periods (Logue, D.M., Madigan, S.M., Melin, A., Delahunt, E., Heinen, M., Donnell, S.M., & Corish, C.A., 2020).

From a sociocultural perspective, Albanian female athletes face challenges related to traditional beliefs on body image, gender roles, and nutrition. These factors, combined with limited institutional support, increase the risk for undiagnosed LEA and subsequent hormonal dysfunction (Caushi Alketa and Latollari, Elda and Cuka, Agron, 2022). The interaction between estradiol and cortisol highlights the importance of hormonal balance for optimal performance and health outcomes. The study emphasizes the need for targeted interventions, including nutritional strategies and psychological support, to mitigate the risks associated with LEA. Promoting education about LEA and RED-S among athletes, coaches, and families is vital to reduce stigma and foster early intervention.

## Conclusion

Low energy availability represents a substantial threat to hormonal regulation, performance, and long-term health among female athletes. Estradiol suppression, coupled with elevated cortisol and reduced thyroid function, contributes to decreased endurance, injury susceptibility, mood disturbances, and impaired recovery. This study emphasizes how important estradiol is for controlling body composition, energy use, and performance in Albanian female elite athletes, especially when low energy availability (LEA) is present. By influencing mitochondrial function and β-adrenergic activity, estradiol promotes lean body mass preservation, promotes favorable

fat distribution, and increases metabolic efficiency. Multidisciplinary support – combining sports medicine, endocrinology, nutrition, and psychology – is essential to restore energy balance and hormonal health.

Addressing the sociocultural elements causing energy shortages also requires culturally appropriate methods, psychological support, and nutritional instruction. In the context of Albanian elite athletes, these risks are compounded by cultural norms, inadequate dietary intake, and limited access to medical and psychological support. Recognizing estradiol as a biomarker for physiological strain should prompt early screening and intervention programs. Individualized care and culturally aware education campaigns should be the top priorities of future programs to lower the prevalence of LEA and improve female athletes' performance and general well-being. Future initiatives ought to concentrate on incorporating multidisciplinary support networks, such as sports psychologists and nutritionists, and utilizing technology to track energy balance and performance indicators in real time. Athletes can optimize their estradiol levels, reduce the risks of LEA, and improve their competitive and overall health by giving priority to these techniques.

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