Low Energy Availability in Athletes

Understanding Undereating and Its Concerns

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Relative Energy Deficiency in Sport (REDs) is a syndrome of impaired physiological function due to low energy availability (LEA) such that there is insufficient energy intake after subtracting the cost of energy expended through exercise. There are no universal criteria to identify an athlete with REDs. Rather, physiological outcomes and functional impairments that occur because of LEA are used for identification purposes. Once an athlete is identified with REDs, treatment should focus on addressing the underlying cause of LEA. This may include increasing energy intake and/or decreasing exercise energy expenditure as well as addressing factors that may exacerbate LEA. Much has been uncovered about the negative consequences of LEA. Early models were for women, whereas newer models include athletes of both sexes. More research is needed to increase the understanding of LEA so that the model of REDs and best practice guidelines to prevent, identify, and treat REDs will continue to evolve. Nutr Today 2023;58:51–57

FROM THE FEMALE ATHLETE TRIAD TO RELATIVE ENERGY DEFICIENCY IN SPORT

Seminal studies in the 1980s demonstrated that female athletes with functional hypothalamic amenorrhea—the absence of menses or irregular menstrual cycles—had reduced bone mineral density (BMD) compared with eumenorrheic athletes[1] and that BMD improved with the resumption of menses.[2] Although the cause of menstrual dysfunction in athletes was unknown and was initially thought to be associated with eating disorders, this was later updated to recognize inadequate energy intake resulting from a variety of causes. Indeed, the term *energy availability* was introduced to sports nutrition,[3] to reflect the energy available to support the body's physiological functions by subtracting the energy expended through exercise from the athlete's total energy intake.[4] Energy availability is calculated mathematically from the following calculation:

$$\text{Energy Availability} = \frac{\text{Energy Intake} - \text{Exercise Energy Expenditure}}{\text{Fat Free Mass}}$$

Energy availability differs to energy balance (energy intake minus total energy expenditure) in that energy balance represents an output from physiological systems and does not consider that physiological systems may be suppressed by inadequate energy intake, which in turn may decrease total energy expenditure.[5] The negative consequences of low energy availability (LEA) were first described by the female athlete triad model as an interrelated occurrence of LEA, impaired bone health, and menstrual dysfunction in female athletes.[6] Later, the International Olympic Committee introduced the expanded model of Relative Energy Deficiency in Sport (REDs) as a syndrome of "impaired physiological function including, but not limited to, metabolic rate, menstrual function, bone health, immunity, protein synthesis and cardiovascular health" underpinned by LEA.[7] The expanded model of REDs was introduced to reflect that LEA can have negative outcomes on a larger range of body systems and is a concern for male athletes as well as female athetles.[7,8] Notably, the intention was not to replace the female athlete triad with REDs but rather to encompass it within a larger model of potential health and performance consequences. More recently, the triad has been updated to include the male athlete.[9] Figure 1 summarizes the evolution of the various models involving LEA in sport.[10] The negative consequences of LEA may also impact those that do not train for a specific sport, such as recreational exercisers,[11] or those with occupations requiring physical work, such as military personnel.[12]

In addition to new insights gained from clinical practice and sports nutrition research, the 2023 update on REDs is considering lessons gleaned from the theory of life history.[13] This branch of evolutionary science proposes that, during periods of inadequate food procurement, human survival is underpinned by the ability to partition energy supplies to the biological processes that are of critical immediate need.[1–3] Indeed, humans are conditioned to adapt to periods of LEA by downregulating biological

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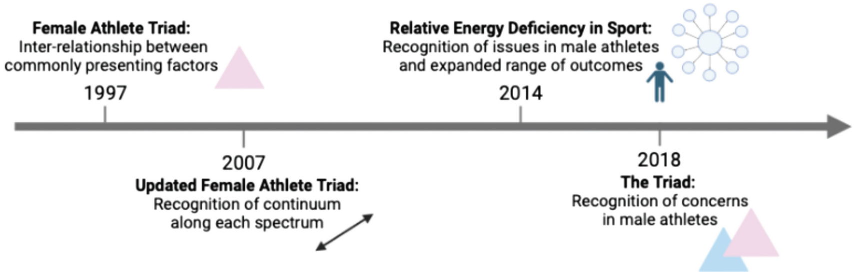

FIGURE 1. Overview of the evolution of models related to energy deficiency in athletes.

processes that are considered at least temporarily unnecessary.[13,14] Some of these perturbations to body systems might be considered mild and/or transient, representing adaptive physiological plasticity. Meanwhile, problematic exposure to LEA, the duration and exposure to which may vary according to characteristics of the individual and the body system, leads to the health and performance impairments described in the REDs and triad models.[8,9]

IDENTIFYING ATHLETES WITH REDS

Early identification of REDs is critical for preventing the numerous health and performance consequences of LEA. Despite LEA being the underlying cause of REDs, directly calculating an athlete's energy availability is not recommended for identification purposes because of the errors and methodological challenges of calculating energy intake, exercise energy expenditure, and fat-free mass.[10,15] Furthermore, we now recognize that there is no single threshold for the magnitude/duration of LEA that is associated with problematic outcomes.[10,15] Rather, validated tools and/or symptoms of LEA should be used for identification purposes. Within the clinical setting, the REDs Clinical Assessment Tool can be used by trained medical professionals to assess an athlete's risk of REDs[16]; an updated version of this will be released with the 2023 REDs update. Although only available for use with women, the Low Energy Availability in Females Questionnaire can also be used to identify athletes who are at an increased risk of LEA and require further assessment.[17] Both of these tools focus on the biochemical markers and functional impairments that may occur because of LEA, such as menstrual dysfunction, reduced or low BMD, and recurring bone stress injuries. Although physique characteristics such as low body weight, low levels of body fat, or weight loss are often identified as being of concern, some athletes with REDs may have a stable and seemingly "normal" body mass. A diagnosis (or a failure to diagnose) should never be assumed solely on body mass and composition. Given the effects of LEA on various metabolic and endocrine systems, biochemical markers such as such as testosterone (male), triiodothyronine, insulinlike growth factor-1, cortisol, and others may assist in developing the picture of REDs.[4,18,19] However, care needs to be taken when using these markers for diagnostic purposes because they may be impacted by factors beyond that of LEA, and these are not always included in routine biochemical assessments. Table 1 highlights functional impairments, biochemical markers, and behavioral and psychological changes that may be used as indicators of LEA. However, there is a need for further research to identify valid and reliable markers of energy status, their thresholds for concern, and strategies to allow differential diagnoses (ie, causes of perturbations unrelated to REDs).

Take-Home Message: Although LEA is the underlying cause of REDs, calculations of energy availability should not be used for identification purposes. Rather, the physiological outcomes and functional impairments that occur because of LEA should be used to identify athletes with REDs.

CAUSES OF LEA

The underlying cause of LEA should be determined in athletes with REDs because this will guide treatment decisions and the need for a multidisciplinary team. Low energy availability may be caused by unintentional undereating, intentional food restriction for performance or health purposes, mismatches between food availability and exercise commitments, and/or pathological eating and exercise behaviors, as highlighted in Figure 2. It is important to note that LEA and subsequent changes in body composition and performance may trigger restrictive eating practices and disordered eating behaviors.[20,21] As such, causes of LEA should not be assumed to occur in isolation.

Unintentional Undereating

Athletes may unintentionally consume insufficient energy leading to the inadvertent development of LEA. Possible

TABLE 1 Indicators Suggestive of Low Energy Availability

Functional impairments	Menstrual dysfunction in women Low sex drive or lack of morning erectile function in men Low bone mineral density or reduced bone mineral density compared with previous measurement Recurring bone stress injuries Low BMI or body fat levels and/or substantial weight loss Reduced body temperature and increased sensitivity to cold Gastrointestinal issues such as constipation or bloating
Biochemical markers	Decreased: testosterone (male), triiodothyronine, insulinlike growth factor 1, insulin, leptin, ferritin Increased: growth hormone, cortisol, LDL cholesterol
Behavioral changes	Restrictive eating behaviors such as cutting out food groups or measuring foods Avoiding food-related social activities and secretive behavior regarding food intake and/or exercise Additional training above what is required and/or inability to take rest days
Psychological changes	Becoming withdrawn and reclusive Anxiety, irritability, and difficulties concentrating Body image dissatisfaction and distortion

Abbreviations: BMI, body mass index. LDL, low-density lipoprotein.

scenarios that may lead to unintentional undereating include the following[10]:

- Increases in training load: Increased exercise energy expenditure does not always lead to a compensatory increase in energy intake, which may be due to hormonal changes in response to exercise that suppresses appetite.
- Poor nutrition literacy: Athletes may have poor nutrition knowledge, including lack of knowledge on how to prepare or choose foods that meet energy requirements.
- Restricted food choices: Athletes who have food intolerances and allergies, or restrict dietary choices because of religious/cultural/ethical considerations (eg, vegetarianism/veganism) or fussy palates, may find it more difficult to meet energy requirements from the available food supply. This is particularly seen when the athlete is outside their usual food environment (eg, travel).
- Small eating windows: Some sports may impede an athlete's ability to consume sufficient energy. For instance, sports with lengthy training sessions may restrict the eating window, or athletes may restrict food intake because of concerns that food will lead to gastrointestinal distress during exercise.
- Mishandled injury: Injured athletes may reduce energy intake because of perceived reductions in energy needs with a reduced training load. Yet, an athlete may actually have increased energy requirements to support injury repair or because of increased energy expenditure due to ambulation (ie, use of crutches) or rehabilitation program.
- Travel or other changes to food environment: Traveling for competition or training camps may lead to insufficient energy intake by interfering with an athlete's normal eating patterns, or foods that an athlete typically consumes may be unavailable.
- Food insecurity: Athletes may not have the financial resources to buy foods or easy access to foods that meet energy requirements. For instance, athletes may spend large portions of their day at training facilities where food may be up-priced and/or only offer food of poor nutritional quality

In the previously mentioned situations, athletes should work with an accredited sports dietitian to address the factors leading to insufficient energy intake. This will likely

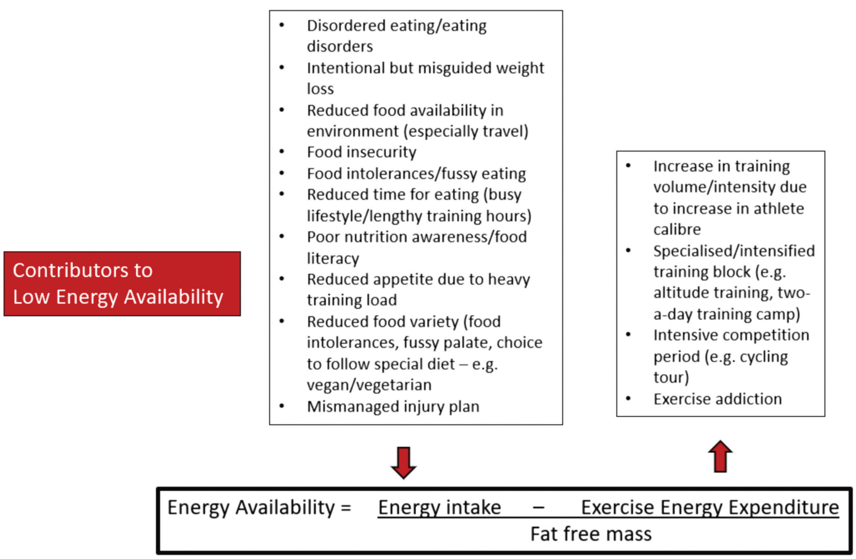

FIGURE 2. Low energy availability may occur in a range of scenarios in which there is a decrease in energy intake and/or an increase in exercise energy expenditure.

include education to increase an athlete's nutrition knowledge and food literacy, and the creation of personalized food plans that take into consideration an athlete's food preferences, unique training situation, and budget. The sports dietitian may also need to work alongside an athlete's coach and support team to implement targeted strategies to increase energy intake, such as making foods that an athlete finds appealing more readily available.

Intentional Food Restriction

Some athletes may restrict food intake with the intention to manipulate body composition for performance and/or health purposes and, in the process, develop LEA. This may be particularly prevalent for sports where a low body mass and/or body fat level may offer a performance advantage, such as the following[22]:

- Gravitational sports: long-distance running, road and mounting cycling, ski jumping, jumping in athletics
- Weight division sports: wrestling, lightweight rowing, judo, boxing
- Aesthetically judged sports: figure skating, diving, gymnastics, synchronized swimming, body building

Athletes seeking to manipulate body composition for performance and/or health purposes should work with an accredited sports dietitian to ensure that targeted weight goals are appropriate and nutritional strategies implemented do not compromise long-term health.

Eating Disorders or Disordered Eating

It is commonly accepted that the energy restriction due to an underlying eating disorder or disordered eating can lead to the development of LEA.[23] Whereas an eating disorder meets the diagnostic criteria according to the *Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition*, disordered eating is problematic eating behaviors that fail to meet these diagnostic criteria.[24] Disordered eating is more prevalent than clinical eating disorders and includes pathogenic behaviors to control weight, preoccupation with “healthy” eating, and/or a cognitive focus on burning calories when exercising.[25] Although eating disorders and disordered eating are also a concern for male athletes, especially those competing in weight-sensitive sports,[26] the relationship between disordered eating and LEA has not been thoroughly examined in male athletes. Clearly, this is an area that needs further research.

Unanswered Increase in Exercise Volume

Most athletes undertake a periodized training program that includes periods of intensified exercise. Although this may be tolerated, when short-lived and supported by a change in dietary intake, some athletes are either unaware of their new energy requirements or unable able to access additional food in their environment. This is often the case when the athlete travels to specialized training camps/competition where there is a change in their food availability (eg, limited catering or financial limits). It may also occur when the athlete moves to a new training squad or increases their sporting commitment and is unaware of new nutritional needs and/or does not experience a commensurate change in appetite.

Pathological Exercise Behaviors

Pathological exercise behaviors, such as compulsive exercise or exercise dependence, can also contribute to the development of LEA. The terms *compulsive exercise* and *exercise dependence* are often used interchangeably despite differences in these behaviors. Compulsive exercise represents an urge to perform exercise with the intent to escape the anxiety that arises from the imagined negative consequences of not exercising, whereas with exercise dependence, exercise is an addictive behavior that is intrinsically motivated through an influence on positive affect.[27] Both exercise dependence and compulsive exercise commonly occur secondary to disordered eating such that exercise is being used as a way to control weight.[28] Although there is evidence that problematic exercise behaviors may lead to the development of LEA,[29,30] few studies have looked at the role of pathological exercise behaviors independent of an eating disorder or disordered eating in the development of LEA. One study found that, for both male and female athletes, only when exercise dependence was secondary to disordered eating was an increased risk of LEA and associated health outcomes seen.[31] Furthermore, athletes with both exercise dependence and disordered eating were at an even greater risk of LEA and associated health outcomes compared with athletes with disordered eating in isolation.[31] As such, when determining underlying causes of LEA in athletes, both an athlete's relationship with food and exercise must be assessed for pathological behaviors.

Take-Home Message: There are multiple causes of LEA in athletes that may co-occur. These include intentional undereating, unintentional undereating, or pathological eating and exercise behaviors. Identifying underlying causes of LEA is essential for implementing treatment strategies.

TREATMENT STRATEGIES

Given that LEA is the underlying cause of REDs, treatment must correct LEA. However, because of the substantial error involved with calculating energy availability and the lack of a validated threshold that is considered "optimal" for athletes, treatment should not be aiming to achieve a specific threshold of energy availability.[32] Rather, treatment should focus more broadly on increasing energy intake and/or reducing exercise energy expenditure.[32] This includes implementing strategies targeting the underlying cause of inadequate energy intake or excessive energy expenditure, as highlighted previously. However, beyond increasing energy availability, treatment strategies may also target factors that exacerbate and/or independently affect the health outcomes of LEA.[32] This may include minimizing within-day energy deficiency, avoiding periods of low carbohydrate availability, reducing fiber intake, and ensuring adequate intake of bone-building nutrients.[32] Examples of these interventions and proposed mechanisms of action are highlighted in Table 2. In addition to these nutritional interventions, athletes with compromised bone health may also consider including mechanical bone stress, such as strength or resistance exercise, within their training program to increase BMD.[33] Replacing energetically demanding aerobic exercise sessions with less energetically demanding strength or resistance training sessions may also aid in the recovery process by decreasing exercise energy expenditure and, in turn, increasing energy availability.[34] Finally, athletes may benefit from the inclusion of therapy, such as cognitive behavioral therapy, to address psychogenic stress that may be contributing to LEA and to assist athletes in making behavioral changes.[8] Treatment will often require a multidisciplinary team of health professionals with ongoing follow-up to ensure progress is being made.[7]

Take-Home Message: Just as calculating energy availability should not be used for diagnostic purposes, achieving a specific threshold of energy availability should not be the goal of REDs treatment. Rather, treatment should focus on more broadly increasing energy intake and/or decreasing training load, and may also include interventions aimed at exacerbating factors of LEA.

TABLE 2 Nutritional Interventions for Treatment of REDs Aimed at Factors That Exacerbate Low Energy Availability

Exacerbating Factor	Mechanism	Nutrition Intervention
Within-day energy deficiency	The more time over 24 h spent in a negative energy deficit is associated with markers of LEA.	Consume adequate energy around exercise Consume breakfast upon waking, and a meal or snack every 3-5 h
Low carbohydrate availability	Low carbohydrate availability may impair bone turnover and immune system function independent of energy availability. Consumption of carbohydrates over isoenergetic amounts of fat results in higher levels of leptin, which plays a critical role in the function of the HPG axis.	Ensure overall daily carbohydrate requirements are being met Ensure adequate carbohydrate intake before, during, and after exercise Undertake specific sessions of training with low glycogen/overnight fasting with care and only when properly integrated into a periodized training program
Excessive fiber intake	High-fiber diet may increase satiety, making it difficult to meet energy requirements. Excessive fiber intake may reduce estrogen reabsorption and contribute to menstrual dysfunction.	Consider replacing high-fiber foods with lower fiber options Limit the consumption of high-fiber foods at meals that may be displacing more energy-dense food options
Inadequate intake of bone-building nutrients	Independent of energy availability may compromise bone health.	Ensure adequate intake of nutrients important for bone health Consider having the vitamin D status of an athlete assessed If insufficient intake of bone-building nutrients in diet, consider supplementation

Abbreviations: HPG, hypothalamic-pituitary-gonadal; LEA, low energy availability; REDs, Relative Energy Deficiency in Sport.

PREVENTION

Creating a healthy sport culture that maintains athletes' physical and mental health is critical for the prevention of REDs. This involves increasing awareness of REDs through education to all involved in athlete care, such as coaches, trainers, and parents, and having a zero-tolerance policy for toxic training environments or practices that include body shaming, overexercising, and underfuelling.[35] Creating a healthy sport culture may involve coaches focusing on enhancing athletic performance via nondieting strategies such as mental approaches, selecting team captains who have a healthy relationship with food and their body, and deemphasizing talk centered around body weight, food restriction, and/or dieting.[36] Finally, coaches should not be involved in assessing the body composition of athletes, but rather, athletes who express a desire to change body composition should be referred to a sports dietitian who can ensure that safe nutrition changes are made.[23]

Take-Home Message: To prevent REDs, all involved in athlete care are responsible for creating a healthy sport culture that ensures athlete health is the top priority.

CONCLUSION AND FUTURE DIRECTION

Much has been uncovered about the implications of LEA on athlete health and performance over the past 40 years. Low energy availability must be taken seriously given the health and performance consequences that could ultimately derail an athlete's career. Despite the considerable research advances within this area, much more is still needed. In particular, research is needed that will lead to a better understanding of the impact of LEA in male athletes and how this differs from female athletes, as well as research that will lead to valid and reliable markers of LEA that can be used for identification purposes. As the understanding of LEA continues to evolve, so will the model of REDs, and best practice guidelines for identification, treatment, and prevention.

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