Low Energy Availability and Relative Energy Deficiency in Sport: What Coaches Should Know

Braeden T. Charlton1,†, Sara Forsyth2 and David C. Clarke1

Abstract
The Female Athlete Triad (Triad) and the more encompassing Relative Energy Deficiency in Sport (RED-S) are disorders caused by low energy availability (LEA). LEA is a state of insufficient energy intake by an athlete relative to their energy expenditure. Persistent LEA results in the deleterious consequences to health and performance that comprise RED-S. With respect to both the Triad and RED-S, researchers have called for more education of those involved with sport, particularly coaches, to help reduce the incidence of these disorders. Recent studies have shown that as few as 15% of coaches are aware of the Triad, with up to 89% unable to identify even one of its symptoms. RED-S is a more recently established concept such that coach knowledge regarding it has only begun to be assessed, but the results of these initial studies indicate similar trends as for the Triad. In this review, we synthesize research findings from 1986 to 2021 that pertains to LEA and RED-S, which coaches should know so they can better guide their athletes.

Keywords
Athlete training load, bone mineral density, female athlete triad, malnutrition, menstrual function, sports nutrition

Introduction
Since 1992, the term Female Athlete Triad (Triad) has been used to describe the combination of amenorrhea, osteoporosis, and disordered eating1,2. In the years following, the Triad has been studied extensively and recently has been redefined to better represent the scope of the disorder. As of 2007, the Triad is described as a disorder that features menstrual dysfunction, altered bone health, and low energy availability (LEA) with or without an eating disorder3. Low energy availability refers to the state of insufficient energy intake by an individual relative to their energy expenditure4.

Cohorts other than elite and competitive female athletes, such as males, recreational athletes and exercisers (using the terminology of McKinney et al.5), can also present with Triad related-symptoms3,6–35. In 2014, the International Olympic Committee produced a consensus statement suggesting that a new term be adopted that encompasses the full scope of this symptomology36–38. The new term, Relative Energy Deficiency in Sport (RED-S), expands on the previous Triad framework by including males, recreational athletes, and exercisers as populations that are susceptible to the LEA-related symptoms. RED-S also includes a range of adverse health and performance outcomes that stem from an LEA state in addition to the already established menstrual irregularities and impaired bone health seen in the Triad framework. While debate persists on adoption of the new term, proponents of both its Triad and RED-S agree that both disorders stem from LEA39.

Recent studies indicate a high prevalence of LEA in athletes; however, the challenge of measuring LEA in free-living athletes implies that current estimates are spuriously low27,40–43.

Reviewers: Tom Love (Swansea University, UK)
Swarup Mukherjee (Nanyang Technological University, Singapore)

1Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby BC V5A 1S6 Canada
2Division of Sport Medicine, Department of Family Practice, Faculty of Medicine, University of British Columbia, Vancouver, BC V6T 1Z3 Canada
†Present address: Department of Human Movement Sciences, Vrije Universiteit, Amsterdam, 1081 BT, Netherlands

Corresponding author:
David C. Clarke, Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby BC V5A 1S6 Canada.
Email: dcclarke@sfu.ca
Similarly, due to its wide range of outcomes, which will be described further in a later section, RED-S is thought to be more prevalent than is currently reported. Given their adverse impact on health and performance, efforts are underway to better understand and prevent these disorders. A lack of coach knowledge regarding these disorders and their damaging consequences is thought to contribute to their prevalence. Several studies have assessed the knowledge of coaches regarding the Triad, including its signs and symptoms and its detrimental consequences to athlete health and performance. Some of these studies reported that fewer than one-quarter of coaches are aware of the Triad. Furthermore, coach knowledge varies by region, gender, and sport-type. Studies investigating coach knowledge of RED-S are only just beginning to emerge, but they report similar trends as those of the Triad. The high prevalence of the Triad and RED-S coupled with the lack of coach knowledge regarding these disorders has motivated researchers to call for more education regarding LEA and its damaging consequences.

In this review, we synthesized evidence from peer-reviewed studies published between 1986 and 2021 that we believe is essential for coaches to know so they can better guide their athletes and prevent LEA. Because it is generally accepted that the Triad represents three specific symptoms of RED-S, we henceforth refer primarily to RED-S, except when referring to studies that were specific to the Triad. This review aims to provide coaches with the scientific basis underlying the concepts of LEA disorders. Specifically, we provide an overview of RED-S, discuss its performance and health outcomes, describe nutritional guidelines to help prevent LEA, and propose strategies for monitoring and supporting athletes at risk of LEA.

The female athlete triad and relative energy deficiency in sport: diagnosis, mechanism, and prevalence

Originally, the diagnosis of the Triad required the athlete to present with the three following conditions: disordered eating, absent menstruation (amenorrhea), and osteoporotic bones. Nowadays, a female presenting with low energy availability, hormone dysfunction, or low bone mineral density, either alone or in combination, is considered to be at risk of the consequences of the Triad. Furthermore, athletes are considered to exist on a continuum that spans from healthy to pathological health and sub-optimal performance (Figure 1). Males can likewise show the signs and symptoms of Triad, with the exception of irregular menstrual patterns. Accordingly, the International Olympic Committee and other sport governing bodies have suggested the adoption of the more inclusive term, RED-S. RED-S is defined as “impaired physiological functioning caused by relative energy deficiency and includes, but is not limited to, impairments of metabolic rate, menstrual function, bone health, immunity, protein synthesis and cardiovascular health.” Standardized methods for diagnosing RED-S have yet to be established. Currently, similar questionnaires to those used in diagnosing the Triad are used for RED-S, given their shared symptomology. RED-S-specific questionnaires are being developed and validated. In clinical settings, the questionnaires are commonly paired with bone density assessment using dual-energy x-ray absorptiometry (DXA) and energy intake assessment, often using food records.

Several challenges hinder the diagnosis of RED-S. The first challenge is the spectrum of dysfunctions that can present and that different individuals exhibit different subsets of dysfunctions (discussed in more detail below). The second challenge is that assessment depends in part on questionnaires and food records completed by the individual. Noncompliance or inaccurate responses provided by the individual can impair accurate assessment. The third challenge is that RED-S-specific questionnaires continue to be developed and validated. Questionnaires currently used for diagnosing RED-S were adapted from those used for diagnosing clinical eating disorders. Since then, several questionnaires have been developed, such as the Low Energy Availability in Females Questionnaire and the Female Athlete Screening Tool. While these questionnaires were useful for diagnosis of RED-S in females, questionnaires for males are just beginning to emerge. For example, the Androgen Deficiency in the Aging Male Questionnaire and the Exercise Dependence Scale have been found to aid the diagnosis of RED-S in males. Recent studies have shown that using a multipronged approach involving questionnaires, DXA scan, and

Figure 1. The signs of the female athlete triad exist on a continuum from healthy to pathological, as demonstrated by the green to red transition, and they are causally associated in the manner indicated by the arrows.
energy intake assessment have proven useful in diagnosing the Triad and RED-S. Additional studies will be needed to validate RED-S diagnostic procedures more comprehensively.

LEA is the underlying mechanism that causes RED-S. 

*Energy availability* is the energy remaining for physiological function once energy expended during exercise has been taken into account. It is calculated using the following equation:

\[
\text{Energy Availability} = \text{Energy Intake} - \text{Exercise Energy Expenditure}
\]

with each term in the equation expressed in units of kilocalories per kilogram of fat-free mass. Those with energy availabilities of less than 30 kcal per kilogram of fat-free mass are at risk of LEA. It has been suggested that males can tolerate lower energy availabilities based on the higher energy needed by the female reproductive system, but limited evidence exists to support this contention. Additionally, a rigorously defined threshold does not yet exist because energy availability is difficult to measure in free-living individuals. LEA is further classified as advertent or inadvertent. Advertent LEA refers to the conscious and deliberate restriction of energy intake or increase in energy expenditure. Inadvertent LEA refers to the unwitting and unintentional failure to consume sufficient energy.

Because of the difficulties in diagnosing LEA and RED-S, estimating the prevalence of these conditions within athletic populations is challenging. Estimates are based on inferences from surrogate measures, such as the prevalence of injuries, physiological dysfunction (i.e., amenorrhea or oligomenorrhea), and physical and behavioural signs, which are commonly associated with LEA. These challenges notwithstanding, the prevalence of LEA and RED-S are likely to be higher than is reported. More than a quarter of athletes are at a moderate to high risk of LEA, while up to 79% of athletes in certain cohorts may have RED-S. Those competing in so-called “lean sports”, in which a higher power-to-body-mass ratio is thought to benefit athletic performance, are at higher risk. Such sports include athletics (track and field), combat sports (e.g., wrestling and judo), cycling, gymnastics, rowing, synchronized swimming, and triathlon. One study estimated that in a cohort of female athletes, 56% of gymnasts, 49% of cross-country runners, and 43% of swimmers were at a moderate to high risk of LEA. In a sample of collegiate distance runners, 45% of males and 41% of females were estimated to have energy availabilities lower than 30 kcal/kg fat-free mass. However, the risk of LEA extends to athletes who might not be stereotypically thought of as high risk. For example, 31% of sprinters at a Canadian university presented with LEA at pre-season testing and 54% presented with at least one LEA symptom at post-season testing. For the Triad, Heikura et al. estimated that 34%, 26%, and 6% of 39 female athletes presented with one, two, or three symptoms of the Triad, respectively.

Observational evidence indicates a relationship between LEA risk and its consequences. For example, cross-country runners in the moderate-risk category for LEA were twice as likely to sustain a bony stress injury, and those in the high-risk category were four times as likely to sustain bony stress injuries. These results emphasize the need for all coaches to be knowledgeable about LEA and RED-S and be vigilant in monitoring their athletes for its presence, even coaches in sports not traditionally considered to be within the “lean sport” category.

**Performance and health impairments of LEA and RED-S**

The key to an athlete’s development is the quality and quantity of training coupled with their ability to adapt to the training. Coaches must understand the intricate interrelationship between these factors and performance. Coaches understandably tend to focus on the training load part of the equation: Achieving ever greater training loads is important for improving athletic performance, especially for athletes with prolonged training histories. Furthermore, training loads are relatively easy to see. Coaches observe athletes training and commonly collect objective data through portable measurement devices such as heart-rate monitors and GPS wristwatches. Higher training loads are implicitly assumed to represent better training.

Despite the perceived benefits to performance from higher training loads, they will only benefit performance if the athlete is capable of physiologically adapting to them. The adaptability of the athlete is much more challenging to assess, with indirect measures such as resting heart rate, athlete perceptions, and heart-rate variability commonly used in practice. Proper nutrition, sleep, stress management, and recovery modalities such as massage are prescribed to maintain or enhance an athlete’s adaptability. However, determining whether the optimal balance of training load and recovery enhancement has been achieved is challenging. Additionally, the coaches’ abilities to observe athletes are generally limited to the sporting environment. If the athlete participates in other sports or activities, then these training loads will accumulate unseen, thus challenging the coach’s ability to accurately monitor training loads. Currently, studies regarding monitoring training loads have been limited to single-sport situations, and there is currently no perfected practice for monitoring multisport athletes who interact with multiple coaching staffs.

LEA limits performance by compromising the body’s ability to adapt to a given training load. Table 1 lists some of the physiological and psychological performance components of LEA that present in individuals with RED-S. The list is neither exhaustive nor universal; other performance outcomes may be caused by LEA, while not all those with RED-S may experience all the listed...
impairments. Generally, more severe LEA and its consequences can cause lost training days due to injury or illness, and lost training days compromise performance. Overall, coaches must internalize these basic considerations: proper training loads combined with adequate nutrition are two critical and inseparable factors for achieving peak athletic performance.

Beyond performance, coaches should adhere to the ethical principle that they “strive to preserve the present and future health and well-being of athletes.” RED-S can have significant and potentially long-term irreversible health consequences for athletes (Figure 2). These health effects centre on three areas: hormone and metabolic function, bone health, and cognitive ability and mental health.

**Hormonal and metabolic function**

Hormones are chemical messengers that help control virtually all bodily functions, including metabolism, muscle and bone mass and function, and cognitive functioning. Hormone physiology is complex, and their effects are not easily understood by those without specialized training in physiology. At minimum, coaches should know that hormone dysfunction is a hallmark of LEA disorders. For those that seek more detail, we describe below dysfunctions with selected hormones, including estrogen, testosterone, leptin, insulin growth factor-1 (IGF-1), growth hormone, cortisol, thyroid hormone, and insulin.

Estrogen and testosterone are important for reproductive functioning and for bone health and metabolic regulation. Therefore, disruptions in these hormones can have widespread detrimental consequences including enhanced injury risk. Estrogen levels in females and testosterone levels in males are lower in those with LEA compared to those who have adequate EA. The hormone leptin regulates reproductive function via stimulation of gonadotropin-releasing hormone. Leptin is secreted by adipocytes (fat cells) and its levels are proportional to fat mass. Athletes with LEA exhibit decreased leptin levels and attendant disruption of reproductive function due to decreased gonadotropin-releasing hormone stimulation.

Growth hormone is required for muscle and bone anabolism (anabolism connotes “assembly” or “building up”, as opposed to catabolism, which connotes “breaking down”). Growth hormone acts via IGF-1, which also acts to regulate growth hormone secretion. Athletes experiencing LEA exhibit elevated growth hormone levels but reduced circulating IGF-1, suggesting that resistance within this pathway has developed during LEA. The overall effect of these changes is decreased muscle synthesis, bone anabolism, growth, and repair.

Cortisol is primarily a catabolic hormone that acts to promote energy supply, in part through muscle protein breakdown and lipolysis (breakdown of fats). Those experiencing LEA exhibit elevated levels of cortisol, which promotes a catabolic state that can restrict muscle glycogen stores, promote proteolysis of muscle tissue and promote resorption of bone tissues, thus increasing risk of injury and illness.

Thyroid hormone controls energy expenditure to ensure sufficient energy for growth and reproduction. It is intimately tied to the reproductive hormones estrogen and testosterone. Thyroid deficiency generally leads to an energy preservation state, in which energy normally reserved for growth and reproduction is reduced and diverted to more vital functions. As such, athletes in LEA states have reduced thyroid hormone levels. These deficiencies result in decreased growth and reproductive function, which is evident when considering the amenorrheic athlete. In this instance, the decrease in thyroid hormone results in a dysregulation of the intricate relationship between thyroid hormone and estrogen production, ultimately resulting in reproductive system impairments.

Insulin is also an anabolic hormone: it activates glucose uptake, glycogen synthesis, protein synthesis, and inhibits

---

**Table 1. Commonly reported performance impairments of RED-S.**

| Component of performance | Effect                                      |
|--------------------------|--------------------------------------------|
| Physiological            | Decreased training response                 |
|                          | Decreased glycogen stores                  |
|                          | Decreased endurance performance            |
|                          | Decreased muscle strength                  |
| Psychological            | Decreased coordination                     |
|                          | Decreased concentration                    |
|                          | Impaired judgment                          |
|                          | Depression                                  |
|                          | Irritability                                |

**Figure 2.** Relative energy deficiency impairs the physiological functions that support athlete growth and development, health, and performance.
protein degradation\textsuperscript{25,116,120,121}. Circulating glucose is the primary source of energy in the body; blood glucose is tightly regulated by insulin and its counteracting hormone, glucagon. By promoting glucose uptake into cells, insulin works to decrease blood glucose. Insulin levels tend to be decreased in those with LEA\textsuperscript{68,74}. Athletes with LEA have lower energy stores and thus a metabolic rate (RMR) tends to decrease\textsuperscript{25}. The RMR is the levels tend to be decreased in those with LEA\textsuperscript{68,74}. Reduced insulin levels are detrimental because it allows for accelerated breakdown of proteins to sustain blood glucose and may result in reduced protein synthesis\textsuperscript{121,122}. The increased breakdown of muscle may increase the risk of injury and reduce strength and performance. If the athlete is injured, the decrease in protein synthesis may potentially prolong recovery and the time taken to return to sport\textsuperscript{36,123–126}.

A notable consequence of LEA is that the resting metabolic rate (RMR) tends to decrease\textsuperscript{25}. The RMR is the energy expended per unit time by the body while in the resting state and results from processes that maintain vital bodily functions such as breathing, cardiac functioning, growth and repair, etc. In LEA, RMR is reduced such that less energy is utilized by the reproductive, growth and repair systems, and energy is conserved for functions necessary for survival\textsuperscript{127,128}. LEA is associated with increased percentage body fat and muscle breakdown\textsuperscript{43,129}. The relative gain in fat may seem paradoxical and the mechanisms remain poorly understood, but it has been reproducibly observed and also occurs in those with anorexia nervosa\textsuperscript{130–134}. Coaches must understand the effects of LEA on metabolic rate and body composition, which underscores that simplistically restricting energy intake as a mechanism for losing weight or body fat is likely to be counterproductive.

Bone health
Peak bone accrual typically occurs between the ages of 18 and 22; however, some studies indicate further accrual into the third decade of life\textsuperscript{135–137}. Athletes who have LEA tend to have altered bone density and geometry due to their inability to produce sufficient levels of regulatory hormones and for those hormones to act appropriately on their targets\textsuperscript{112,114,138–140}. These hormones can act either directly (i.e. IGF-1, leptin, and triiodothyronine) or indirectly (i.e. estrogen, testosterone) on bone metabolism. In some cases of LEA, particularly those involving intentional restricted caloric intake, athletes may not get sufficient calcium and vitamin D, both of which are essential to generating new bone\textsuperscript{85,141,142}. As a result, 12–45% of athletes with LEA tend to have lower bone mineral density, between one and two standard deviations below the population average\textsuperscript{38,114,139,143,144}. Depending on the duration of their LEA, athletes may also present with altered bone geometry compared to their healthy peers, particularly decreased trabecular area in weight-bearing bones such as the pelvis\textsuperscript{38,139,140}. The lower bone density and weakened structure can lead to increased risk of bony stress injuries that in turn can lead to stress fractures, which results from imbalanced bone resorption and bone formation\textsuperscript{79,114,145}. Such scenarios are especially problematic for female athletes because they tend to be at higher risk of developing bony stress injuries compared to their male counterparts due to anatomical and hormonal differences\textsuperscript{146–149}. Athletes sustaining these injuries lose training time. Additionally, recurrent bony stress injury history is predictive of future bone-related injuries\textsuperscript{150–154}.

Cognitive ability and mental health
Those with LEA exhibit decreased cognitive ability, decreased attention, and higher risk of anxiety\textsuperscript{34}. A survey of 1000 participants admitted to a Boston hospital with sport-related injuries found that those classified as having LEA were 4.3-times more likely to report impaired judgment, 1.6-times more likely to report feeling uncoordinated, and twice as likely to report problems concentrating\textsuperscript{83}. In addition, those experiencing iron deficiency as a result of poor nutrition habits associated with RED-S were more likely to present with cognitive impairments, depression, and anxiety due to hypothryoid-like states seen with LEA\textsuperscript{155}.

Nutritional practices to help prevent LEA and RED-S
The most effective approach to mitigate the adverse performance and health consequences of RED-S is through proper nutrition. Many academic and sport organizations, including the International Olympic Committee, recommend that coaches educate themselves about proper nutrition. We further emphasize that athletes and their parents should also be educated in sports nutrition. A detailed review of sport nutrition is beyond the scope of this review, but we direct the reader to the following credible and readily available scientific references:

- American College of Sports Medicine, Academy of Nutrition and Dietetics, and Dieticians of Canada joint position stand on Nutrition and Athlete Performance (2016)\textsuperscript{156}
- International Society for Sport Nutrition Exercise & Sports Nutrition Review Update: Research & Recommendations (2018)\textsuperscript{157}

Coaches working with youth athletes are further referred to review articles focused on youth athletes (cf. refs\textsuperscript{158,159}). Drawing upon these sources, we discuss below some general principles for ensuring sufficient nutrition for athletes.

First, athletes must obtain sufficient total energy (Calories) from food. Energy requirements depend on sex,
body mass, biological age, and energy expenditure from training and competing. Pubescent and pre-pubescent children have greater energy requirements due to the increased energy need to support growth. The accepted daily energy requirement for female athletes aged 11 to 18 is approximately 2200 kcal, while that for males of the same age range is 2500–3000 kcal. Following puberty, the energy needs of a person will show a minor increase, primarily due to the increase in body mass. These energy needs are generally maintained through early adulthood until approximately 40-years of age, at which point they steadily decrease to 2000–2500 kcal in the elderly years.

Daily energy needs vary considerably across individuals and depend proportionally on body mass and physical activity levels. We therefore emphasize that the cited numbers serve as a general guide only and that those performing higher levels of activity will have correspondingly higher energy needs.

Second, athletes must obtain sufficient macronutrients, i.e., carbohydrate, fat, and protein. Athletes are advised to consume 5–12 g of carbohydrate per kilogram body mass per day, depending on the nature of their training activities. Those training at moderate-to-high intensities for 1–3 h per day should consume closer to 5–8 g per kilogram body mass, whereas those training at moderate-to-high intensities 4–5 h per day should consume closer to 9–12 g per kilogram body mass.

Athletes may consume inadequate carbohydrate for several reasons. First, carbohydrate-restricted diets are popular for weight loss. Second, athletes may restrict carbohydrate as a stimulus to promote enhanced fat oxidation and endurance. While some studies show that low-carbohydrate diets can spare glycogen and enhance fat oxidation, these adaptations fail to improve performance. In fact, performance often decreases due to impaired ability to use carbohydrate as a fuel, which is necessary for exercise at higher intensities. Third, some athletes may inadvertently limit their carbohydrate intake by avoiding certain foods due to gastrointestinal distress. Such impairments to carbohydrate intake can lead to lower quality training and negatively impact bone mineral density by potentially increasing concentrations of molecules associated with bone resorption.

Protein is essential for muscle repair and other anabolic processes. Athletes should consume 1.2–1.7 g of protein per kilogram body mass per day. If an athlete is injured, it is recommended that the athlete consumes 1.2–1.5-times more protein than usual, because doing so can help accelerate recovery and prevent muscle breakdown due to inactivity. In general, athletes consume close to the recommended protein requirements; however, in the case of those who follow restricted diets (e.g., vegan, gluten free), athletes may not obtain enough.

Fat intake is important because lipid molecules are critical components of cells and they contribute to numerous aspects of physiology including the immune response, absorption of fat-soluble vitamins (A, D, and E), and hormone regulation. It is therefore suggested that fat intake be approximately 15–30% of daily total caloric intake. Generally, eating a well-balanced diet will result in sufficient fat intake. However, fat intake may be inadequate in those who consume inadequate total energy or who follow restrictive diets.

Third, athletes must obtain adequate micronutrients such as minerals and vitamins. While there are many micronutrients, we focus on the following three minerals: Calcium, phosphorus, and iron. Calcium and phosphorus are critically important for bone formation because bone material consists of the compound calcium phosphate. During puberty, when the rate of bone accrual is heightened, both minerals are needed in higher amounts. Athletes should consume higher amounts of calcium because transient periods of minor bone loss followed by bone growth occur in response to physical activity. Additionally, calcium is important for nervous system functioning and muscle activation.

Iron is an essential mineral involved in hemoglobin synthesis, thyroid metabolism, and energy production. Those deficient in iron typically exhibit extreme fatigue, decreased aerobic performance, and impaired immune functioning. Iron deficiency is common in athletes, particularly those competing in endurance sports. Prevalence rates range from zero to 17% in males and 24–42% in females. However, some studies report that up to 65% of males and 86% of females present with deficient iron levels.

Vitamin D is critical to bone formation due to its integral role in calcium absorption. Without it, sufficient calcium cannot be absorbed to maintain proper bone health. Vitamin D is also important to maintaining nervous system and muscular functioning. Athletes living and training in certain geographic regions, specifically in areas above 40° North, may get insufficient sunlight. Sunlight is a major factor for Vitamin D synthesis, such that supplementation may be required for those who get insufficient exposure to sunlight. Furthermore, it has been shown that Vitamin D deficiency is more prevalent in the winter and spring seasons compared to summer and fall. Food sources rich in Vitamin D include fortified dairy products, egg products, and fatty fishes.

National food guidelines provide practical recommendations for consuming sufficient nutrition. For example, national nutrition guidelines commonly emphasize eating plenty of fruits and vegetables, choosing whole grain foods, and eating sufficient protein. In addition, it is recommended to limit the consumption of processed foods in favour of home-cooked meals. Food that is less processed contains more vitamins and minerals for a given number of calories. Moreover, including a broad variety of foods within the diet is recommended. An idea to promote variety in meals is to make the meal as colourful as possible. Implementing this rule of thumb associates with healthier food choices and decreased consumption of...
sugary foods. Consuming diverse foods maximizes the chances of consuming sufficient micronutrients and antioxidants. Proper hydration is important because dehydration can impair performance and recovery from training. Water is the recommended drink of choice; consuming sugary drinks and alcohol should be limited because of their deleterious effects on performance in the short term and health in the long term.

Fourth, athletes should eat the right foods at the right time. Effective timing ensures not only that an athlete is properly fueled for workouts and competition, but also recovers efficiently from the workloads. For pre-training or pre-competition nutrition, athletes should consume approximately 1–4 g of carbohydrates per kilogram body mass (normally around 200 g of carbohydrates), about 10–30 g of protein (depending on whether the exercise is more endurance focused or power/resistance focused), and limited fat to avoid gastrointestinal distress. Meals should be consumed one to four hours prior to training or competition, with the time proportional to the size of the meal. Post-training, athletes should consume about 60–120 g of carbohydrate within 30 min of exercise to promote glycogen replenishment. In addition, it is proposed an “anabolic window” exists up to 48 h after exercise, during which protein intake is likely most effective in enhancing muscle protein synthesis and impairing muscle breakdown. It has therefore been recommended that athletes consume 20–30 g of protein sometime between one hour before training to one hour after training. While this consumption of protein in close proximity to training is encouraged by the American College of Sports Medicine and the International Society of Sports Nutrition, evidence exists that total protein intake over 24-h periods may be more influential than the timing of protein intake to enhancing muscle protein synthesis.

Throughout a competitive season, training loads are commonly periodized in order to maximize sport adaptation. Phases generally include preparatory, pre-competition and competition phases, which vary in training load durations and intensities. Likewise, the nutritional demands of each of these phases will vary with the demands of the training sessions. As such, it has been suggested that nutrition periodization may be crucial in some sporting environments to help maximize adaptation. Macro-periodization refers to month-to-month nutritional strategies, whereas micro-periodization refers to within-day or week nutrition. Due to complexities of various training programs, no single optimal strategy can be prescribed. However, some suggested strategies that may be relevant over a wide range of sports include reducing the amount of fibrous foods within 1–2 h of training sessions to avoid gut disturbances, prioritizing appropriate carbohydrate and protein intake immediately following sessions, and incorporating snacks throughout a 24-h period to avoid the depletion of energy stores.

Finally, coaches must understand that body composition management should be undertaken only for elite-level athletes using scientifically sound approaches assisted by qualified professionals. Indeed, losing weight is neither easy to achieve nor necessarily beneficial because of the compensation in resting metabolic rate, the detrimental effects of reduced carbohydrate on performance, and the loss of muscle mass. Hence, any attempt to lose weight must be informed by these consequences, and evidence-based guidelines are available for doing so. For example, adequate protein intake is essential to support protein synthesis and maintenance of muscle mass. In addition, the frequency of

Figure 3. Guidelines for nutrition and body composition across the stages of athlete development. Adapted from Ackerman (2020).
protein consumption should increase \(^{201,203,204}\). By spreading protein intake throughout the day, it is thought that a sufficient pool of protein and amino acids will be available to support protein synthesis \(^{201,203,205,206}\).

### Monitoring athletes for risk of LEA

To help athletes avoid the pitfalls of RED-S, coaches should be aware of the signs and symptoms indicating those at risk of LEA. Because RED-S can affect multiple organ systems, many signs and symptoms can manifest, which can make detection challenging. One particularly prevalent sign of RED-S is that of decreased performance. Some athletes may initially experience a temporary period of improved performance prior to a prolonged period of underperformance. The degree of performance hindrance can range from minor to severe. Other noteworthy signs include injury and illness. Athletes with LEA are at higher risk of sustaining stress fractures and muscle strains, and report illnesses more frequently compared to their peers \(^{64,99,213}\).

Aspects of an athlete’s medical history may associate with a higher risk of RED-S. A plethora of behavioural changes can accompany LEA. Behaviours regarding feeding and diet, exercise and physical activity, and self criticism are especially common (Table 2) \(^{6,25,38,42,64,98,208,209}\). The behaviours exhibited by those with RED-S may be similar to those exhibited by those with disordered eating \(^{6,64,210,211}\). Other signs include social withdrawal and depression \(^{6,64,212}\).

Importantly, athletes are likely to exhibit a unique subset of the possible signs \(^{3,38}\). For example, Athlete A may present with irregular menstruation, evidence of disordered eating, and have a long history of musculoskeletal injuries. Athlete B may present with minor social withdrawal, feelings of fatigue, and rigidity in their routine. For this reason, coaches should be attentive to their athletes and maintain effective communication, so that some of these patterns can be more readily identified. If an athlete begins to show some of these signs and symptoms, then coaches should immediately take steps to address and manage the problem. The next section describes management strategies for at-risk athletes.

### Supporting athletes at risk of LEA

Even if preventive measures are instituted, some athletes may still be at risk for LEA, such that coaches may find themselves having to support an athlete with RED-S. The first step the coach should take in supporting an athlete at risk is to document the signs and symptoms that they

| Class of signs                                      | Signs                                                                 | \(^{64,99,213}\) |
|---------------------------------------------------|-----------------------------------------------------------------------|-----------------|
| Decreased performance                             | Underperformance, possibly preceded by an acute period of improved performances | 201,203,204,213 |
|                                                   | Decreased neuromuscular performance                                   |                 |
| Increased or persistent injuries                  | Evidence of reduced bone mineral density                               | 42,112,114,139  |
| Medical history                                   | History of injuries                                                   | 64              |
|                                                   | History of depression                                                 | 6,64            |
| Behaviours related to diet and eating             | Manipulation of food intake that is unnecessary for health, sport performance, or appearance | 64,215          |
|                                                   | Unusual weighing behaviour (i.e. excessive weighing, refusal to weigh for health or safety reasons, negative reaction to being weighed) | 9               |
|                                                   | Secretive eating or ritualistic eating patterns                       | 6,209           |
|                                                   | Chewing and/or spitting out large amounts of food while avoiding swallowing | 6              |
|                                                   | Compulsiveness and rigidity regarding eating and exercising           | 6,209           |
|                                                   | Binge eating, and agitation when binging is interrupted               | 2               |
|                                                   | Substance abuse, whether legal, illegal, prescribed, over the counter medications, or other substances | 6              |
| Behaviours related to purging                     | Evidence of vomiting unrelated to illness or due to purposeful purging | 2               |
|                                                   | Use of laxatives/diuretics                                            |                 |
|                                                   | Compulsive exercising with the intent of purging                      | 2               |
|                                                   | Drinking excess water as a form of purging                            | 216,217         |
| Behaviours related to exercise and physical activity | Excessive or obligatory exercise beyond that recommended for training or performance | 2               |
|                                                   | Exercising while injured despite medically prescribed activity restriction |                 |
| Physical signs                                    | Frequent weight fluctuations or pressure (either internal or external) to lose weight | 6,64           |
|                                                   | Restlessness, difficulty relaxing                                     | 6               |
| Self criticism behaviours, social withdrawal      | Self criticism, especially concerning body weight, size, and shape, and performance | 64              |
|                                                   | Body image dissatisfaction                                            | 64              |
|                                                   | Claims of feeling fat despite being thin                               | 6,64            |
| Inappropriate coaching behaviour                  | Comments by other coaches regarding an athlete’s body composition, shape or weight | 94,218–220     |
have observed. The next step is to speak with the athlete (and their parents if a youth) stating that their observations are consistent with the athlete being at risk of having RED-S. The coach should then encourage the athlete to consult with a sports medicine physician, who are the healthcare professionals with specialized training needed to manage these disorders. The physician can then assess the athlete and propose an appropriate plan of action based on the athlete’s needs.

There are several key points to emphasize in supporting at-risk athletes:

- The earlier the plan of action is implemented, the sooner the athlete may be able to return to form, and the lower the risk of long-term impacts on physical and mental health.
- The coach should communicate with the athlete in a manner that preserves their dignity. These conversations are personal and should be conducted privately away from other athletes.
- Coaches should respect the athlete’s autonomy; it is their choice to seek medical attention. Coaches can merely encourage the athlete to seek medical attention.
- Coaches must respect their scope of practice; they are not medical professionals, and they cannot diagnose illnesses, injuries, or disorders.

For athletes with LEA, effective coach-athlete (and, if appropriate, coach-parent) communication is imperative. The communication style and methods employed by the coach can have negative or positive effects. Negative coach commentary regarding the athlete’s performance, body composition, or attitude may propel the athlete to adopt pathological habits to attempt to reduce the negative commentary. In contrast, positive commentary used to support an athlete can assist them to avoid pathological behaviours. Indeed, it appears that carefully considered word choices and appropriate conflict resolution methods are beneficial for supporting athletes. Coach communication can be difficult to navigate, and coaches often use a mix of positive and negative strategies. However, strategies for positive coach-athlete/parent communication have been proposed, such as encouraging open dialogue, not dismissing or denying athlete concerns, and encouraging the athlete to seek medical advice particularly relating to weight issues and mental health.

After an athlete has sought medical advice, the coach can support the athlete in adhering to the recovery plan. In particular, the coach should adhere to medically recommended activity restrictions as part of the return-to-sport protocol when the athlete has returned to training. In doing so, the coach assists the athlete to avoid relapse, injury, or other problems that would further set the athlete back.

The International Olympic Committee has recently released a clinical assessment tool and a return-to-sport model that practitioners may use to aid in the athlete’s return to training and competing. In this model, the athlete is stratified into one of three risk levels:

1. Low risk: the athlete has an appropriate physique that is managed without undue stress or unhealthy diet or training strategies.
2. Moderate risk: the athlete may have prolonged or severe low-energy availability marked by low BMI, low bone mineral density, abnormal menstruation, or a disordered eating pattern; and
3. High risk: the athlete is diagnosed with eating disorders or other serious medical conditions (psychological or physiological) relating to low energy availability.

High-risk athletes may be encouraged to abstain from training and competition until they progress into a moderate- or low-risk category. Even within the moderate category, training and competitions restrictions may be imposed, with return to sport requiring clearance by a physician.

The management of an athlete at risk of RED-S should include a multidisciplinary healthcare approach. The coach may work with the overseeing physician or allied health professionals to develop an appropriate return-to-sport plan. In addition, the athlete may face stressors from within the sport context or external to it that may trigger relapse. The coach is well positioned to help minimize stressors from within the sport, such as the pressure to perform and relationships with teammates and team personnel. Coaches should encourage safe return and discourage premature sport or competition participation.

Coaches should understand the critical role they play in the athlete’s recovery process. Athletes tend to follow their coaches’ advice more so than that from parents or physicians. This degree of influence is important for athlete development but can be detrimental if coaches provide advice and influence that conflicts with that of the overseeing physician. It is the coach’s primary responsibility to protect the health of the athlete and to help the athlete adhere to the recovery program prescribed by the physician.

Conclusion

All athletes are at risk of LEA, particularly those who compete in sports that benefit from a high power-to-weight ratio. Although injury and illness are more common outcomes of LEA, the potential long-term damages to physiological development incurred from unfavourable metabolism and altered hormone profiles are particularly concerning. Coaches are uniquely positioned to help prevent athletes from entering LEA states, because they prescribe athlete training loads and observe and communicate with athletes in the daily training environment. Similarly, coaches play a crucial role in supporting athletes with LEA disorders back to health. However, coaches can
only fulfill these prevention and support roles if they are well educated with regards to LEA and RED-S and are mindful of their influence on athlete behaviour. The information provided within this review should help coaches to play integral roles in reducing RED-S incidence.

Acknowledgements

We thank Trent Stellingwerff and Sharleen Hoar of the Canadian Sport Institute Pacific for providing critical commentary of earlier versions of the review.

ORCID ID

David C. Clarke https://orcid.org/0000-0002-1520-5426

References

1. Yeager KK, Agostini R, Nativ A, et al. The female athletic triad: Disordered eating, amenorrhea, and osteoporosis. Med Sci Sport Exerc 1993; 25: 775–777. doi:10.1097/00005768-199305000-00023

2. Drinkwater BL, Sherman RT, Sundgot-Borgen J, et al. International Olympic committee medical commission working group women in sport. Position Stand on the Female Athlete Triad 2005. https://stillmed.olympic.org/Documents/Reports/EN/en_report_917.pdf

3. Nativ A, Loucks AB, Manore MM, et al. The female athlete triad. Med Sci Sports Exerc 2007; 39: 1–13.

4. Loucks AB, Kiens B and Wright HH. Energy availability in athletes. J Sports Sci 2011; 29: S7–S15.

5. McKinney J, Velghe J, Fee J, et al. Defining athletes and exercisers. 2019.

6. Bonci CM, Bonci LJ, Granger LR, et al. National athletic trainers’ association position statement: Preventing, detecting, and managing disordered eating in athletes. J Athl Train 2008; 43: 80–108.

7. De Souza MJ, Arce JC, Pescatello LS, et al. Gonadal hormones and semen quality in male runners. Int J Sport Med 1994; 15: 383–391.

8. Hackney AC. Effects of endurance exercise on the reproductive system of men: the “exercise-hypogonadal male condition.”. J Endocrinol Invest 2008; 31: 932–938.

9. Brownlee KK, Moore AW and Hackney AC. Relationship between circulating cortisol and testosterone: influence of physical exercise. J Sport Sci Med 2005; 4: 76–83.

10. Melin A, Torstveit MK, Burke L, et al. Disordered eating and eating disorders in aquatic sports. Int J Sport Nutr Exerc Metab 2014; 24: 450–459.

11. Tenforde AS, Barrack MT, Nativ A, et al. Parallels with the female athlete triad in male athletes. Sport Med 2016; 46: 171–182.

12. Chapman J and Woodman T. Disordered eating in male athletes: a meta-analysis. J Sports Sci 2016; 34: 101–109.

13. Tenforde AS, Nativ A, Ackerman K, Barrack MT and Frederickson M. Optimising bone health in the young male athlete. Br J Sports Med 2017; 51: 148–149.

14. Hooper DR, Kraemer WJ, Saenz C, et al. The presence of symptoms of testosterone deficiency in the exercise-hypogonadal male condition and the role of nutrition. Eur J Appl Physiol 2017; 117: 1349–1357.

15. Hackney AC. Hypogonadism in exercising males: dysfunction or adaptive-regulatory adjustment? Front Endocrinol (Lausanne) 2020; 11: 1–16.

16. Wong HK, Hoermann R and Grossmann M. Reversible male hypogonadotrophic hypogonadism due to energy deficit. Clin Endocrinol (Oxf) 2019; 91: 3–9.

17. Smathers AM, Bemben MG and Bemben DA. Bone density comparisons in male competitive road cyclists and untrained controls. Med Sci Sports Exerc 2009; 41: 290–296.

18. McCormack WP, Shoeppe TC, LaBrie J, et al. Bone mineral density, energy availability, and dietary restraint in collegiate cross-country runners and non-running controls. Eur J Appl Physiol 2019; 119: 1747–1756.

19. De Souza MJ, Koltun KJ and Williams NI. What is the evidence for a triad-like syndrome in exercising men? Curr Opin Physiol 2019; 10: 27–34.

20. Pedlar CR, Newell J and Lewis NA. Blood biomarker profiling and monitoring for high-performance physiology and nutrition: current perspectives, limitations and recommendations. Sports Med 2019; 49: 185–198.

21. De Souza MJ, Koltun KJ and Williams NI. The role of energy availability in reproductive function in the female athlete triad and extension of its effects to Men: an initial working model of a similar syndrome in male athletes. Sport Med 2019; 49: 125–137.

22. Lane AR, Hackney AC, Smith-Ryan A, et al. Prevalence of low energy availability in competitively trained male endurance athletes. Med 2019; 55: 1–11.

23. Heikura IA, Quod M, Strobel N, et al. Alternate-Day Low energy availability during spring classics in professional cyclists. Int J Sports Physiol Perform 2019; 14: 1233–1243.

24. Torstveit MK, Fahrenholtz I, Stenqvist T, et al. Within-Day energy deficiency and metabolic perturbation in male endurance athletes. Int J Sport Nutr Exerc Metab 2018: 419–427.

25. Elliott-sale KJ, Tenforde AS, Parziale AL, et al. Endocrine effects of relative energy deficiency in sport. Int J Sport Nutr Exerc Metab 2018; 28: 335–349.

26. Burke LM, Close GL, Lundy B, et al. Relative energy deficiency in sport in male athletes: a commentary on its presentation Among selected groups of male athletes. Int J Sport Nutr Exerc Metab 2018; 28: 364–374.

27. Heikura IA, Uusitalo AL, Stellingwerff T, et al. Low energy availability Is difficult to assess but outcomes have large impact on bone injury rates in elite distance athletes. Int J Sport Nutr Exerc Metab 2018; 28: 403–411.

28. Rector RS, Rogers R, Ruebel M, et al. Lean body mass and weight-bearing activity in the prediction of bone mineral density in physically active men. J Strength Cond Res 2009; 23: 427–435.

29. Mathisen TF, Heia J, Raustol M, et al. Physical health and symptoms of relative energy deficiency in female fitness athletes. Scand J Med Sci Sport 2020; 30: 135–147.

30. Hetland ML, Haarbo J and Christiansen C. Low bone mass and high bone turnover in male long distance runners. J Clin Endocrinol Metab 1993; 77: 770–775.

31. Artioli G, Gualano B, Franchini E, et al. Prevalence, magnitude, and methods of rapid weight loss among judo competitors. Med Sci Sport Exerc 2010; 42: 436–442.
32. Filare E, Rouveix M, Bouget M, et al. Prévalence des troubles du comportement alimentaire chez le sportif. *Sci Sport* 2007; 22: 135–142.
33. Filare E, Rouveix M, Pannafieux C, et al. Eating attitudes, perfectionism and body-esteem of elite male judoists and cyclists. *J Sport Med Sci* 2007; 6: 50–57.
34. Sundgot-Borgen J and Torstveit MK. Aspects of disordered eating continuum in elite high-intensity sports. *Scand J Med Sci Sport* 2010; 20: 112–121.
35. Scofield KL and Hecht S. Bone health in endurance athletes: runners, cyclists, and swimmers. *Curr Sports Med Rep* 2012; 11: 328–334.
36. Mountjoy M, Sundgot-Borgen J, Burke L, et al. The IOC consensus statement: beyond the female athlete triad–relative energy deficiency in sport (RED-S). *Br J Sports Med* 2014; 48: 491–497.
37. Mountjoy M, Sundgot-Borgen J, Burke L, et al. Authors’ 2015 additions to the IOC consensus statement: relative energy deficiency in sport (RED-S). *Br J Sports Med* 2015; 49: 417–420.
38. Mountjoy M, Sundgot-Borgen J, Burke L, et al. IOC Consensus statement on relative energy deficiency in sport (RED-S): 2018 update. *Br J Sports Med* 2018; 52: 687–697.
39. Statuta SM. The female athlete triad, relative energy deficiency in sport, and the male athlete triad: the exploration of low-energy syndromes in athletes. *Curr Sports Med Rep* 2020; 19: 43–44.
40. Logue DM, Madigan SM, Melin A, et al. Low energy availability in athletes 2020: an updated narrative review of prevalence, risk, within-day energy balance, knowledge, and impact on sports performance. *Nutrients* 2020; 12: 1–20.
41. Schofield KL, Thorpe H and Sims ST Where are all the men? Low energy availability in male cyclists: a review. *Eur J Sport Sci* 2020; 1–12.
42. Sygo J, Coates AM, Sesbreno E, et al. Prevalence of indicators of low energy availability in elite female sprinters. *Int J Sport Nutr Exerc Metab* 2018; 28: 490–496. doi:10.1123/ijsnem.2017-0397
43. Mountjoy M, Sundgot-Borgen J, Burke L, et al. International Olympic committee (IOC) consensus statement on relative energy deficiency in sport (RED-S): 2018 update. *Int J Sport Nutr Exerc Metab* 2018; 28: 316–331.
44. Rogers MA, Appaneal RN, Hughes D, et al. Prevalence of impaired physiological function consistent with relative energy deficiency in sport (RED-S): an Australian elite and pre–elite cohort. *Br J Sports Med* 2021; 55: 38–45.
45. Lassiter JW and Watt CA. Student Coaches’ knowledge, attitudes, skills, and behaviors regarding the female athlete triad. *Phys Educ* 2007; 64: 142–151.
46. Turk JC, Prentice WE, Chappell S, et al. Collegiate Coaches’ knowledge of eating disorders. *J Athl Train* 1999; 34: 19–24.
47. Friderer JE, Mottinger SG and Palao JMJM. Collegiate Coaches’ knowledge of the female athlete triad in relation to sport type. *J Sports Med Phys Fitness* 2016; 56: 287–294.
48. Pantano KJ. Current knowledge, perceptions, and interventions used by collegiate coaches in the U.S. Regarding the prevention and treatment of the female athlete triad. *N Am J Sports Phys Ther* 2006; 1: 195–207. http://www.ncbi.nlm.nih.gov/pubmed/21522222. Accessed October 8, 2017.
49. Sherman RT, Thompson RA, Dehass D, et al. NCAA Coaches survey: the role of the coach in identifying and managing athletes with disordered eating. *Eat Disord* 2005; 13: 447–466.
50. Mukherjee S, Chand V, Wong XX, et al. Perceptions, awareness and knowledge of the female athlete triad amongst coaches - Are we meeting the expectations for athlete safety? *Int J Sport Sci Coach* 2016; 11: 545–551.
51. Brown KN, Wengreen HJ and Beals KA. Knowledge of the female athlete triad, and prevalence of triad risk factors among female high school athletes and their coaches. *J Pediatr Adolesc Gynecol* 2014; 27: 278–282.
52. Pantano KJ. Knowledge, attitude, and skill of high school coaches with regard to the female athlete triad. *J Pediatr Adolesc Gynecol* 2017; 30: 540–545.
53. Warner AG, Rizzarelli KH, Davis S, et al. Awareness of the female athlete triad in NCAA cross country coaches. *Med Sci Sport Exerc* 2019; 51: 70.
54. Kroshus E, Sherman RT, Thompson RA, et al. Gender differences in high school Coaches’ knowledge, attitudes, and communication about the female athlete triad. *Eat Disord* 2014; 22: 193–208.
55. Wasserfurth P, Palmowski J, Hahn A, et al. Reasons for and consequences of Low energy availability in female and male athletes: social environment, adaptations, and prevention. *Sport Med - Open* 2020; 6: 313–315. doi:10.1123/ijsnem.2018-0149
56. Mountjoy ML, Burke LM, Stellingwerff T, et al. Relative energy deficiency in sport: The tip of an iceberg. *Int J Sport Nutr Exerc Metab* 2018; 28: 313–315. doi:10.1123/ijsnem.2018-0149
57. Joy E, De Souza MJ, Nattiv A, et al. Female athlete triad coalition consensus statement on treatment and return to play of the female athlete triad. *Curr Sports Med Rep* 2014; 13: 219–232.
58. Loveless MB. Female athlete triad. *Curr Opin Obstet Gynecol* 2017; 29: 301–305.
59. Logue DM, Madigan SM, Melin A, et al. Self-reported reproductive health of athletic and recreationally active males in Ireland: potential health effects interfering with performance. *Eur J Sport Sci* 2020: 1–10.
60. Melin A, Tornberg ÅB, Skouby S, et al. The LEAF questionnaire: a screening tool for the identification of female athletes at risk for the female athlete triad. *Br J Sports Med* 2014; 48: 540–545.
61. Koltun KJ, Williams NI and Souza MD. Female athlete triad cumulative risk assessment tool: proposed alternative scoring strategies. *Appl Physiol Nutr Metab* 2020; 45: 1324–1331.
62. Koltun KJ, Strock NCA, Southmayd EA, et al. Comparison of female athlete triad coalition and RED-S risk assessment tools. *J Sports Sci* 2019; 37: 2433–2442. doi:10.1080/02640414.2019.1640551
63. Burke LM, Lundy B, Fahrenholz IL, et al. Pitfalls of conducting and interpreting estimates of energy availability in free-living athletes. *Int J Sport Nutr Exerc Metab* 2018; 28: 350–363.
64. Javed A, Tebben PJ, Fischer PR, et al. Female athlete triad and Its components: toward improved screening and management. *Mayo Clin Proc* 2013; 88: 996–1009.
65. Fahrenholtz IL, Sjödin A, Benardot D, et al. Within-day energy deficiency and reproductive function in female endurance athletes. *Scand J Med Sci Sport* 2018; 28: 1139–1146.

66. Torstveit MK, Fahrenholtz IL, Lichtenstein MB, et al. Exercise dependence, eating disorder symptoms and biomarkers of relative energy deficiency in sports (RED-S) among male endurance athletes. *BMJ Open Sport Exerc Med* 2019; 5: e000439. doi:10.1136/bmjsem-2018-000439

67. Loucks AB and Verdon M. Slow restoration of LH pulsatility by refeeding in energetically disrupted women. *Am J Physiol* 1998; 275: R1218–R1226.

68. Loucks AB and Thuma JR. Luteinizing hormone pulsatility is disrupted at a threshold of energy availability in regularly menstruating women. *J Clin Endocrinol Metab* 2003; 88: 297–311.

69. Melin AK, Heikura IA, Tenforde A, et al. Energy availability in athletics: health, performance, and physique. *Int J Sport Nutr Exerc Metab* 2019; 29: 152–164.

70. O’Leary TJ, Wardle SL and Greeses JP. Energy deficiency in soldiers: the risk of the athlete triad and relative energy deficiency in sport syndromes in the military. *Front Nutr* 2020; 7: 142–160.

71. Bronson F. Mammalian Reproduction: An ecological perspective. *Biol Reprod* 1985; 32: 1–26.

72. Fagerberg P. Negative Consequences of Low Energy Availability in Natural Male Bodybuilding: A Review. *Int J Sport Nutr Exerc Metab* 2018; 28: 385–402.

73. Jurov I, Keay N, Had V, Spudi D and Rauter S. Relationship between energy availability, energy conservation and cognitive restraint with performance measures in male endurance athletes. *J Int Soc Sports Nutr* 2021; 18: 1–10.

74. Koehler K, Gibbs JC, Zinner C, et al. Low energy availability in exercising men is associated with reduced leptin and insulin but not with changes in other metabolic hormones. *J Sport Sci* 2016; 34: 1921–1929.

75. Langan-evans C, Germaine M, Artukovic M, et al. The psychological and physiological consequences of Low energy availability in a male combat sport athlete. *Med Sci Sport Exerc* 2021; 53: 673–683.

76. Beermann BL, Lee DG, Almstedt HC, et al. Nutritional intake and energy availability of collegiate distance runners. *J Am Coll Nutr* 2020; 39: 747–755.

77. Dipla K, Kraemer RR, Constantin MW, et al. Relative energy deficiency in sports (RED-S): elucidation of endocrine changes affecting the health of males and females. *Hormones (Athens)* 2021; 20: 35–47

78. Logue D, Madigan SM, Delahunt E, et al. Low energy availability in athletes: a review of prevalence, dietary patterns, physiological health, and sports performance environment exposure. *Sport Med* 2018; 48: 73–96.

79. Tenforde AS, Carlson JL, Chang A, et al. Association of the female athlete triad risk assessment stratification to the development of bone stress injuries in collegiate athletes. *Am J Sports Med* 2017; 45: 302–310.

80. Meng K, Qiu J, Benardot D, et al. The risk of low energy availability in Chinese elite and recreational female aesthetic sports athletes. *J Int Soc Sports Nutr* 2020; 17: 13–20.

81. 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: 628–633.

82. Beals KA. Eating behaviors, nutritional status, and menstrual function in elite female adolescent volleyball players. *J Am Diet Assoc* 2002; 102: 1293–1296.

83. Torstveit MK and Sundgot-Borgen J. Participation in leanness sports but not training volume is associated with menstrual dysfunction: a national survey of 1276 elite athletes and controls. *Br J Sports Med* 2005; 39: 141–147.

84. Torstveit MK and Sundgot-Borgen J. The female athlete triad exists in both elite athletes and controls. *Med Sci Sports Exerc* 2005; 37: 1449–1459.

85. Sundgot-Borgen J and Torstveit MK. The female football player, disordered eating, menstrual function and bone health. *Br J Sports Med* 2007; 41: 68–72.

86. Cobb KL, Bachrach LK, Greendale G, et al. Disordered eating, menstrual irregularity, and bone mineral density in female runners. *Med Sci Sports Exerc* 2003; 35: 711–719.

87. Hopkinson RA and Lock J. Athletics, perfectionism, and disordered eating. *Eat Weight Disord - Stud Anorexia, Bulim* Obes 2004; 9: 99–106.

88. Rosen LW, McKeag DB, Hough DO, et al. Pathogenic weight-control behavior in female athletes. *Phys Sportsmed* 1986; 14: 79–86.

89. Dummer GM, Rosen LW, Heusner WW, et al. Pathogenic weight-control behaviors of young competitive swimmers. *Phys Sportsmed* 1987; 15: 75–86.

90. Rosen LW and Hough DO. Pathogenic weight-control behaviors of female college gymnasts. *Phys Sportsmed* 1988; 16: 140–144.

91. Beals KA and Hill AK. The prevalence of disordered eating, menstrual dysfunction, and low bone mineral density among US collegiate athletes. *Int J Sport Nutr Exerc Metab* 2006; 16: 1–23.

92. Sundgot-Borgen J and Torstveit MK. Prevalence of eating disorders in elite athletes is higher than in the general population. Clinical journal of sport medicine. *Off J Can Acad Sport Med* 2004; 14: 25–32.

93. Torstveit MK and Sundgot-Borgen J. The female athlete triad: are elite athletes at increased risk? *Med Sci Sports Exerc* 2005; 37: 184–193.

94. Sundgot-Borgen J, Meyer NL, Lohman TG, et al. How to minimise the health risks to athletes who compete in weight-sensitive sports review and position statement on behalf of the Ad Hoc research working group on body composition, health and performance, under the auspices of the IOC medical commission. *Br J Sports Med* 2013; 47: 1012–1022.

95. Smith DJ. A framework for understanding the training process leading to elite performance. *Sport Med* 2003; 33: 1103–1126.

96. Robson-Ansley PJ, Gleeson M and Ansley L. Fatigue management in the preparation of Olympic athletes. *J Sci Sports* 2009; 27: 1409–1420.

97. Raysmith BP and Drew MK. Performance success or failure is influenced by weeks lost to injury and illness in elite Australian track and field athletes: a 5-year prospective study. *J Sci Med Sport* 2016; 19: 778–783.

98. Mountjoy M, Sundgot-Borgen J, Burke L, et al. Relative energy deficiency in sport (RED-S) clinical assessment tool (CAT). *Br J Sports Med* 2015; 49: 421–423.
99. Keay N, Francis G and Hind K. Low energy availability assessed by a sport-specific questionnaire and clinical interview indicative of bone health, endocrine profile and cycling performance in competitive male cyclists. BMJ Open Sport Exerc Med 2018; 4: e000424–e000431.

100. Bomba M, Corbetta F, Bonini L, et al. Psychopathological traits of adolescents with functional hypothalamic amenorrhea: a comparison with anorexia nervosa. Eat Weight Disord - Stud Anorex Bulim Obes 2014; 19: 41–48.

101. Coaching Association of Canada. Coaching association of Canada (CAC) code of conduct with disciplinary procedures. Canada: Coaching Association of Canada, 2020:1–9.

102. Slater J, McLay-Cooke R, Brown R, et al. Female recreational exercisers at risk for Low energy availability. Int J Sport Nutr Exerc Metab 2016; 26: 421–427.

103. Gibson MES, Fleming N, Zuijdijk C, et al. Where have the periods gone? The evaluation and management of functional hypothalamic amenorrhoea. JCRPE J Clin Res Pediatr Endocrinol 2020; 12: 18–27.

104. Gibney J, Healy M-LL and Sönksen PH. The growth hormone/insulin-like growth factor-I axis in exercise and sport. Endocr Rev 2007; 28: 603–624.

105. Roemmich JN, Richmond EJ and Rogol AD. Consequences of exercise-associated low testosterone and its related symptoms. J Endocrinol Invest 2001; 24: 708–715.

106. Hooper D, Tenforde A and Hackney A. Treating exercise-associated low testosterone and its related symptoms. Phys Sportsmed 2018; 46: 427–434.

107. Nakamura T, Imai Y, Matsumoto T, et al. Estrogen prevents bone loss via estrogen receptor a and induction of Fas ligand in osteoclasts. Cell 2007; 130: 811–823.

108. Rettberg JR, Yao J and Diaz Brinton R. Estrogen: a master regulator of bioenergetic systems in the brain and body. Front Neuroendocrinol 2015; 35: 8–30.

109. Köhn FM. Testosterone and body functions. Aging Male 2006; 9: 183–188.

110. Zhang Y and Chua SJ. Leptin function and regulation. Compr Physiol 2017; 130: 811–823.

111. Friedman JM. Leptin and the regulation of body weight. Keio J Med 2011; 60: 1–9.

112. Southmayd EA, Williams NI, Mallinson RJ, et al. Energy deficiency suppresses bone turnover in exercising women with menstrual disturbances. J Clin Endocrinol Metab 2019; 104: 3131–3145.

113. Warren MP. Endocrine manifestations of eating disorders. J Clin Endocrinol Metab 2011; 96: 333–343.

114. Papageorgiou M, Dolan E, Elliott-Sale KJ, et al. Reduced energy availability: implications for bone health in physically active populations. Eur J Nutr 2018; 57: 847–859.

115. Areta JL, Taylor HL and Koehler K. Low energy availability: history, definition and evidence of its endocrine, metabolic and physiological effects in prospective studies in females and males. Eur J Appl Physiol 2020; 121: 1–21.

116. Alves J, Toro V, Barrientos G, Bartolomé I, Muñoz D and Maynar M. Hormonal changes in high-level aerobic male athletes during a sports season. Int J Environ Res Public Health 2020; 17: 1–12.

117. Kanaka-Gantenbein C. The impact of exercise on thyroid hormone metabolism in children and adolescents. Horm Metab Res 2005; 37: 563–565.

118. Erdoğan R. Effects of endurance workouts on thyroid hormone metabolism and biochemical markers in athletes. Broad Res Artif Intell Neurosci 2020; 11: 136–146.

119. Vanheest JL, Rodgers CD, Mahoney CE, et al. Ovarian suppression impairs sport performance in junior elite female swimmers. Med Sci Sports Exerc 2013; 46: 156–166.

120. Goodpaster BH, He J, Watkins S, et al. Skeletal muscle lipid content and insulin resistance: evidence for a paradox in endurance-trained athletes. J Clin Endocrinol Metab 2011; 93: S52–S59.

121. Dimitriadis G, Mitrou P, Lambadiari V, et al. Insulin effects in muscle and adipose tissue. Diabetes Res Clin Pract 2011: 93: S52–S59.

122. Müestu J, Eliakim A, Jürième J, et al. Anabolic and catabolic hormones and energy balance of the male bodybuilders during the preparation for the competition. J Strength Cond Res 2010; 24: 1074–1081.

123. Areta JL, Burke LM, Camera DM, et al. Reduced resting skeletal muscle protein synthesis is rescued by resistance exercise and protein ingestion following short-term energy deficit. Am J Physiol - Endocrinol Metab 2014; 306: E989–E997.

124. Tipton KD. Nutritional support for exercise-induced injuries. Sport Med 2015; 45: 93–104.

125. Tipton KD. Dietary strategies to attenuate muscle loss during recovery from injury. Nestlé Nutrition Institute Workshop Series 2013; 75: 51–61.

126. Wall BT, Morton JP and van Looon LJC. Strategies to maintain skeletal muscle mass in the injured athlete: nutritional considerations and exercise mimetics. Eur J Sport Sci 2015; 15: 53–62.

127. Wade GN and Schneider JE. Metabolic fuels and reproduction in female mammals. Neurosci Biobehav Rev 1992; 16: 235–272.

128. Wade GN, Schneider JE and Li HY. Control of fertility by metabolic cues. Am J Physiol - Endocrinol Metab 1996; 270.

129. Deutz RC, Benardot D, Martin DE and Cody MM. Relationship between energy deficits and body composition in elite female gymnasts and runners. Med Sci Sports Exerc 2000; 32: 659–668.

130. Zamboni M, Armellini F, Turcato E, et al. Body fat distribution before and after weight gain in anorexia nervosa. Int J Obes 1997; 21: 33–36.

131. Müller W, Fürhapter-rieger A, Lackner S, et al. Novel approaches for the assessment of relative body weight and body fat in diagnosis and treatment of anorexia nervosa: a cross-sectional study. Clin Nutr 2019; 38: 2913–2921.

132. Hübel C, Yilmaz Z, Schaumberg KE, et al. Body composition in anorexia nervosa: meta-analysis and meta-regression of cross-sectional and longitudinal studies. Int J Eat Disord 2019; 52: 1205–1223.

133. Fazeli PK and Klibanski A. The paradox of marrow adipose tissue in anorexia nervosa. Bone 2019; 118: 47–52.

134. Fazeli PK, Faje AT, Bredella MA, et al. Changes in marrow adipose tissue with short-term changes in weight in premenopausal women with anorexia nervosa. Eur J Endocrinol 2019; 180: 189–199.
Heikura IA, Burke LM, Hawley JA, et al. A short-term ketogenic diet impairs markers of bone health in response to exercise. *Front Endocrinol (Lausanne)* 2020; 10: 1–10.

Shaw G, Serpell B and Baar K. Rehabilitation and nutrition protocols for optimising return to play from traditional ACL reconstruction in elite rugby union players: a case study. *J Sports Sci* 2019; 37: 1794–1803.

Masson G and Lamarche B. Many non-elite multisport endurance athletes do not meet sport nutrition recommendations for carbohydrates. *Appl Physiol Nutr Metab* 2016; 41: 728–734.

Cialdella-Kam L, Kulpins D and Manore MM. Vegetarian, gluten-free, and energy restricted diets in female athletes. *Sports* (Basel) 2016; 4: 1–12.

Bass SL. The structural adaptations of cortical bone to loading during different stages of maturation. *J Musculoskelet Neuronal Interact* 2003; 3: 345–347.

Hart NH, Nimphius S, Rantalainen T, et al. Mechanical basis of bone strength: influence of bone material, bone structure and muscle action. *J Musculoskelet Neuronal Interact* 2017; 17: 114–139.

Karami M, Calvo B, Zohoor H, et al. Assessing the role of Ca2+ in skeletal muscle fatigue using a multi-scale continuum model. *J Theor Biol* 2019; 461: 76–83.

Hinton PS. Iron and the endurance athlete. *Appl Physiol Nutr Metab* 2014; 39: 1012–1018.

Denis RS and Conway JL. Iron deficiency and aerobic endurance performance in a female club runner. *Sci Sports* 2019; 34: 45–51.

Gropper SS, Blessing D and Dunham K, Barksdale JM. Iron status of female collegiate athletes involved in different sports. *Biol Trace Elem Res* 2006; 109: 1–14. doi:10.1385/BTER:109:1:901.

McKay AKA, Pyne DB, Burke LM, et al. Iron metabolism: interactions with energy and carbohydrate availability. *Nutrients* 2020; 12: 1–16.

Koehler K, Braun H, Achtzehn S, et al. Iron status in elite young athletes: gender-dependent influences of diet and exercise. *Eur J Appl Physiol* 2012; 112: 513–523.

Shoemaker ME, Gillen ZM, Mckay BD, et al. High prevalence of poor iron Status Among 8- to 16-year-Old youth athletes: interactions Among biomarkers of iron, dietary intakes, and biological maturity high prevalence of poor iron Status Among 8- to 16-year-Old youth athletes: interactions Among. *J Am Coll Nutr* 2020; 39: 155–162.

Farrokhyar F and Tabasinejad R. Prevalence of vitamin D inadequacy in athletes: a systematic-review and meta-analysis. *Sport Med* 2015; 45: 365–378.

Health Canada. Canada’s Dietary Guidelines. 2019. https://food-guide.canada.ca/sites/default/files/artifact-pdf/CDG-EN-2018.pdf.

Drewnowski A. Nutrient density: addressing the challenge of obesity. *Br J Nutr* 2018; 120: 8–14.

Renner B, König LM and Renner B. Colourful = healthy? Exploring meal colour variety and its relation to food consumption. *Food Qual Prefer* 2018; 64: 66–71.

Casa DJ, Cheuvront SN, Galloway SD, et al. Fluid needs for training, competition, and recovery in track-and-field athletes. *Int J Sport Exerc Metab* 2019; 29: 175–180.

Orr S, Imperlini E, Nigro E, et al. Role of functional beverages on sport performance and recovery. *Nutrients* 2018; 10: 1–21.

Goulet ED. Dehydration and endurance performance in competitive athletes. *Nutr Rev* 2012; 70: S132–S136.

Areta L, Burke LM, Ross ML, et al. Timing and distribution of protein ingestion during prolonged recovery from resistance exercise alters myofibrillar protein synthesis. *J Physiol* 2013; 591: 2319–2331.

Phillips SM and Loon LV. Dietary protein for athletes: from requirements to optimum adaptation. *J Sport Sci* 2011; 29: S29–S38.

Aragon AA and Schoenfeld BJ. Nutrient timing revisited: is there a post-exercise anabolic window? *J Int Soc Sports Nutr* 2013; 10: 1–11.

Jäger R, Kerksick CM, Campbell BI, et al. International society of sports nutrition position stand: protein and exercise. *J Int Soc Sports Nutr* 2017; 14: 1–25.

Pablo J, Javier V and Jes D. Hematological and running performance modification of trained athletes after reverse vs. Block training periodization. *Int J Environ Res Public Health* 2020; 17: 1–11.

Wetmore AB, Moquin PA, Carroll KM, et al. The effect of training Status on adaptations to 11 weeks of block periodization training. *Sports* 2020; 8: 1–12.

Mettler S, Mitchell N and Tipton KD. Increased protein intake reduces lean body mass loss during weight loss in athletes. *Med Sci Sport Exerc* 2010; 42: 326–337.

Stellingwerff T. Case study: body composition periodization in an Olympic-level female middle-distance runner over a 9-year career. *Int J Sport Nutr Exerc Metab* 2018; 28: 428–433.

Stellingwerff T, Peeling P, Garvican-Lewis LA, et al. Nutrition and altitude: strategies to enhance adaptation, improve performance and maintain health: a narrative review. *Sport Med* 2019; 49: 169–184.

Burke LM, Jones AM, Jeukendrup AE, et al. Contemporary nutrition strategies to optimize performance in distance runners and race walkers. *Int J Sport Nutr Exerc Metab* 2019; 29: 117–129.

Manore MM. Weight management for athletes and active individuals: a brief review. *Sport Med* 2015; 45: 83–92.

Phillips SM. A brief review of higher dietary protein diets in weight loss: a focus on athletes. *Sport Med* 2014; 44: S149–S153.

Hector AJ and Phillips SM. Protein recommendations for weight loss in elite athletes: a focus on body composition and performance. *Int J Sport Nutr Exerc Metab* 2018; 28: 170–177.

Manore MM. Weight management in the performance athlete. *Nutr Coach Strateg to Modul Train Effic* 2013; 75: 123–133.

Nieuwenhuizen A, Tom D, Snensen S, et al. Dietary protein, weight loss, and weight maintenance. *Annu Rev Nutr* 2009; 29: 21–41.

Ackerman KE, Stellingwerff T, Elliott-Sale KJ, et al. # REDS (relative energy deficiency in sport): time for a re-Clusion in sports culture and systems to improve athlete health and performance. *Br J Sports Med* 2020; 54: 369–370.

Torstveit MK and Sundgot-borgen J. The female athlete triad: are elite athletes at increased risk? *Med Sci Sport Exerc* 2004; 37: 184–193.
208. Thein-Nissenbaum J and Hammer E. Treatment strategies for the female athlete triad in the adolescent athlete: current perspectives. Open Access J Sport Med 2017; 8: 85–95.

209. Selby CLB and Reel JR. A Coach’s Guide to identifying and helping athletes with eating disorders A Coach’s Guide to identifying and helping athletes with eating disorders. J Sport Psychol Action 2011; 2: 100–112.

210. Melin A, Tornberg ÅB, Skouby S, et al. Energy availability and the female athlete triad in elite endurance athletes. Scand J Med Sci Sports 2015; 25: 610–622.

211. Robertson S and Mountjoy M. A review of prevention, diagnosis, and treatment of relative energy deficiency in sport in artistic (synchronized) swimming. Int J Sport Nutr Exerc Metab 2018; 28: 375–384.

212. Sundgot-Borgen J. Risk and trigger factors for the development of eating disorders in female elite athletes. Med Sci Sports Exerc 1994; 26: 414–419.

213. Thein-Nissenbaum JM and Carr KE. Physical therapy in sport female athlete triad syndrome in the high school athlete. Phys Ther Sport 2011; 12: 108–116.

214. Tornberg ÅB, Melin A, Johansson A, et al. Reduced neuromuscular performance in amenorrheic elite endurance athletes. Med Sci Sport Exerc 2017; 49: 2478–2485.

215. Gibbs JC, Williams NI, Scheid JL, et al. The association of a high drive for thinness with energy deficiency and severe menstrual disturbances: confirmation in a large population of exercising women. Int J Sport Nutr Exerc Metab 2011; 21: 280–290.

216. Hew-Butler T, Smith-Hale V, Pollard-McGrandy A, et al. Of mice and Men - The physiology, psychology, and pathology of overhydration. Nutrients 2019; 11: 1–14.

217. Ahmedi L and Goldman MB. Primary polydipsia: update. Best Pract Res Clin Endocrinol Metab 2020; 34: 101469.

218. Plateau CR, McDermott HJ, Arcelus J, et al. Identifying and preventing disordered eating among athletes: perceptions of track and field coaches. Psychol Sport Exerc 2014; 15: 721–729.

219. Jones R, Glintmeyer N and McKenzie A. Slim bodies, eating disorders and the coach-athlete relationship: A tale of identity creation and disruption. Int Rev Socio Psychol 2005; 40: 377–391.

220. Paphathomas A and Lavallee D. Narrative constructions of anorexia and abuse: an athlete’s Search for meaning in trauma. J Loss Trauma 2012; 17: 293–318.

221. U.S. Center for SafeSport. Safesport code for the U.S. Olympic and Paralympic Movement. United States of America: U.S. Center for SafeSport; 2021: 1–45.

222. Safe4Athletes. Handbook: Local sports club policies and procedures designed to provide athletes with a safe and positive environment free of sexual abuse, bullying and sexual harassment. In: Safe4Athletes, P.O. Box 650 Santa Monica, CA 90406, Safe4Athletes.org.

223. Freedman J, Hage S and Quatromoni PA. Eating disorders in male athletes: factors associated With onset and maintenance. J Clin Sport Psychol 2021; 1–22.

224. Plateau CR, Arcelus J, McDermott HJ, et al. Responses of track and field coaches to athletes with eating problems. Scand J Med Sci Sports 2015; 25: e240–e250.