International Journal of Sport Nutrition and Exercise Metabolism, 2019, 29, 152-164
https://doi.org/10.1123/ijsnem.2018-0201

Human Kinetics
SCHOLARLY REVIEW

Energy Availability in Athletics: Health, Performance, and Physique

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The reported prevalence of low energy availability (LEA) in female and male track and field athletes is between 18% and 58% with the highest prevalence among athletes in endurance and jump events. In male athletes, LEA may result in reduced testosterone levels and libido along with impaired training capacity. In female track and field athletes, functional hypothalamic amenorrhea as consequence of LEA has been reported among 60% of elite middle- and long-distance athletes and 23% among elite sprinters. Health concerns with functional hypothalamic amenorrhea include impaired bone health, elevated risk for bone stress injury, and cardiovascular disease. Furthermore, LEA negatively affects recovery, muscle mass, neuromuscular function, and increases the risk of injuries and illness that may affect performance negatively. LEA in track and field athletes may occur due to intentional alterations in body mass or body composition, appetite changes, time constraints, or disordered eating behavior. Long-term LEA causes metabolic and physiological adaptations to prevent further weight loss, and athletes may therefore be weight stable yet have impaired physiological function secondary to LEA. Achieving or maintaining a lower body mass or fat levels through long-term LEA may therefore result in impaired health and performance as proposed in the Relative Energy Deficiency in Sport model. Preventive educational programs and screening to identify athletes with LEA are important for early intervention to prevent long-term secondary health consequences. Treatment for athletes is primarily to increase energy availability and often requires a team approach including a sport physician, sports dietitian, physiologist, and psychologist.

***Keywords**:* eating disorders, injury, relative energy deficiency in sports, weight loss

Track and field athletes have intense physiological demands and require optimized nutrition (Burke et al., 2019; Slater et al., 2018; Stellingwerff et al., 2018; Sygo et al., 2019). Track and field athletes may experience low energy availability (LEA) due to disordered eating (DE) behavior, inadvertently due to lack of appetite or poor nutritional knowledge, or intentionally to achieve a discipline-specific physique to optimize performance (Burke et al., 2018c; Melin et al., 2015; Mooses & Hackney, 2017; Sygo et al., 2018). LEA may result in adverse health outcomes, increased risk of musculoskeletal injuries, and impaired athletic performance (Figure 1; De Souza et al., 2014; Mountjoy et al., 2018; Nattiv et al., 2007). The purpose of this review is to describe LEA and potential physiological and psychological consequences in the context of athletics and to provide recommendations regarding prevention, early detection, and treatment to achieve safe participation in sport for optimal health and performance.

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Low Energy Availability

Energy availability (EA) reflects the difference in energy intake and exercise energy expenditure in relation to fat-free mass (FFM) (Loucks, 2014). Although studies have been unable to determine optimal EA in athletes, EA of at least 45 kcal/kg FFM/day for sedentary eumenorrheic normal weight women (Loucks, 2014) and 40 kcal/kg FFM/day for exercising men (Koehler et al., 2016) appears to be a threshold to ensure optimal EA for physiological functions (Table 1). Clinical studies on eumenorrheic subjects have reported that even a short period of EA (5 days) <30 kcal/kg FFM/day causes severe endocrine and metabolic alterations (Figure 1; Ihle & Loucks, 2004; Loucks & Thuma, 2003). In female athletes,

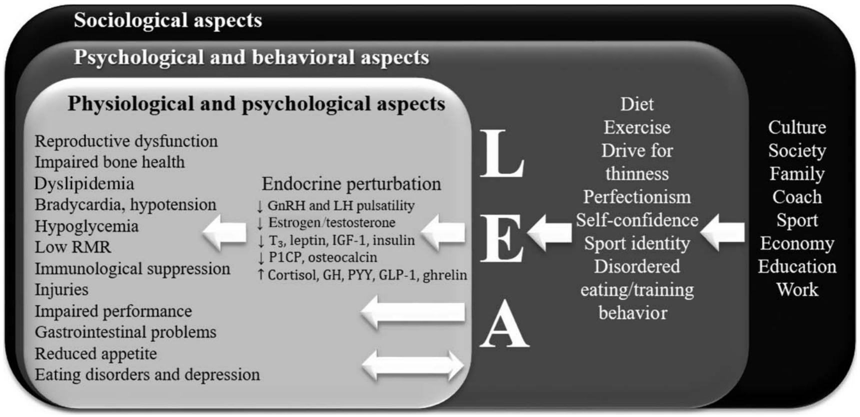

Figure 1 — Potential cause and effect diagram of LEA in athletes. The figure illustrates examples of sociological, psychological, and behavioral causes of LEA, and its potential physiological and psychological effects in athletes described in the literature (Burke et al., 2018, 2018c, De Souza et al., 2014; Elliott-Sale et al., 2018; Ihle & Loucks, 2004; Laughlin & Yen, 1996; Loucks, 2014; Loucks & Thuma, 2003; Melin et al., 2015; Mountjoy et al., 2015, 2018; Nattiv et al., 2007; Rickenlund et al., 2005; Thompson et al., 1993; Tornberg et al., 2017; Turton et al., 2017). Low substrate and nutrient availability negatively affect cognitive and physical function and health as well as performance both directly and indirectly. LEA causes endocrine changes that increase the risk for reproductive and endothelial dysfunction, dyslipidemia, gastrointestinal problems, reduced appetite, injuries, impaired bone health, and immunological suppression. Gastrointestinal problems, reduced appetite, disordered eating, or compulsive exercise behavior as well as depression can precede or be caused by LEA illustrated by the double-headed arrow. GnRH = gonadotropin-releasing hormone; LEA = low energy availability; LH = luteinizing hormone; T_3 = triiodothyronine; IGF-1 = insulin-like growth factor 1; P1CP = carboxy-terminal propeptide of Type I procollagen in serum; GH = growth hormone; PYY = peptide YY; GLP-1 = glucagon-like peptide-1; RMR = resting metabolic rate.

Table 1 Classification of Energy Availability Levels With Examples of Calculation for a Hypothetical Male and Female Athlete

Energy availability	Comments	Example 1: Male athlete: 75 kg; 69 kg FFM (8% body fat) Training at moderate intensity ~1.5–2 hr/day	Example 2: Female athlete: 60 kg; 49 kg FFM (18% body fat) Training at moderate intensity ~1.5–2 hr/day
>40 kcal/kg FFM (males) >45 kcal/kg FFM (females)	High EA: For healthy weight gain or weight maintenance	EEE = 1,500 kcal/day EI = **4,600 kcal/day** EA = (4,600 − 1,500)/69 = 45 kcal/kg FFM/day	EEE = 1,000 kcal/day EI = **3,500 kcal/day** EA = (3,500 − 1,000)/49 = 51 kcal/kg FFM/day
≥40 kcal/kg FFM (males) ≥45 kcal/kg FFM (females)	Optimal EA: For weight maintenance providing adequate energy for all physiological functions. During periods with injury with alternative or rehabilitation training at low/moderate intensity ~1.5 hr/day	EEE = 1,500 kcal/day EI = **4,250 kcal/day** EA = (4,250 − 1,500)/69 = 40 kcal/kg FFM/day EEE = 750 kcal/day EI = **3,500 kcal/day** EA = (3,500 − 750)/69 = 40 kcal/kg FFM/day	EEE = 1,000 kcal/day EI = **3,200 kcal/day** EA = (3,200 − 1,000)/49 = 45 kcal/kg FFM/day EEE = 500 kcal/day EI = **2,700 kcal/day** EA = (2,700–500)/49 = 45 kcal/kg FFM/day
30–40 kcal/kg FFM (males) 30–45 kcal/kg FFM (females)	Subclinical LEA: May be tolerated for short periods during a well-constructed weight-loss program	EEE = 1,500 kcal/day EI = **4,000 kcal/day** EA = (4,000 − 1,500)/69 = 36 kcal/kg FFM/day	EEE = 1,000 kcal/day EI = **2,700 kcal/day** EA = (2,700 − 1,000)/49 = 35 kcal/kg FFM/day
<30 kcal/kg FFM	Clinical LEA: Health implications with impairment of many body systems including training adaptation and performance	EEE = 1,500 kcal/day EI = **3,500 kcal/day** EA = (3,500 − 1,500)/69 = 29 kcal/kg FFM/day	EEE = 1,000 kcal/day EI = **2,300 kcal/day** EA = (2,300 − 1,000)/49 = 27 kcal/kg FFM/day

Note. All numbers regarding EI are in bold. EA = energy availability; EEE = exercise energy expenditure; EI = energy intake; LEA = low energy availability; FFM = fat-free mass.

EA <30 kcal/kg FFM/day is typically defined as clinical LEA and EA between 30 and 45 kcal/kg FFM/day as subclinical LEA (Table 1; De Souza et al., 2014; Melin et al., 2015). However, studies on free-living athletes have failed to find clear thresholds or associations between EA and objective measures of energy conservation or health impairment, such as disruption to metabolic hormones (Heikura et al., 2018; Koehler et al., 2013) and menstrual dysfunction (Melin et al., 2015; Williams et al., 2015). Initially, LEA leads to a negative energy balance and thereby weight loss because the body's energy reserves (e.g., adipose tissue and body proteins) substantially contribute to fuel needs. However, long-term LEA causes metabolic and physiological adaptations in order to reduce total energy expenditure to prevent further weight loss and promote survival, whereby the body obtains a new energy balance steady state (Loucks, 2014). Therefore, an athlete may be weight stable and not excessively low in body mass or body fat levels yet have impaired physiological function secondary to LEA (Burke et al., 2018c; Loucks, 2014).

Athletics consists of a wide array of disciplines that vary significantly in physiological requirements, training characteristics, and optimal physique (Table 2; Burke et al., 2019; Slater et al., 2018; Stellingwerff et al., 2018; Sygo et al., 2019). Middle- and long-distance athletes tend to be small and lean; high jumpers are usually tall and lean; and power athletes (sprints, long and triple jump, pole vault, heptathlon, and decathlon) are both lean and more muscular and powerful. In contrast, throwers tend to be larger with higher adiposity.

The mismatch between energy intake and exercise energy expenditure that causes LEA in athletes may occur intentionally in order to optimize body mass or body composition for competition, to avoid weight gain during injury and illness or due to eating disorders (EDs) or DE behavior. Several potential reasons may explain inadvertent LEA such as large energy needs and suppressed appetite during periods of high-intensity training, especially when combined with adherence to ultrahealthy or "clean" eating with low energy density diets (Burke et al., 2018c; Melin et al., 2016). Energy intake may be suboptimal due to other factors including lack of financial or time resources as well as cultural beliefs (Burke et al., 2018). Dietary aspects other than LEA may also affect physiological function such as extreme dietary fiber intake (Melin et al., 2016) and suboptimal within-day energy balance. Recent studies reported that despite similar 24-hr EA and energy balance, female endurance athletes with functional hypothalamic amenorrhea (FHA) spent more time in a catabolic state compared with eumenorrheic athletes (Fahrenholtz et al., 2018) and demonstrate increased catabolic markers in male endurance athletes (Torstveit et al., 2018).

Prevalence of LEA, DE, and EDs in Athletics

Underreporting or undereating are well-documented behaviors during prospective dietary recording and can therefore explain some of the discrepancies between reported energy intakes and energy needs in athletes and hence result in a potentially false positive diagnosis of LEA (Burke et al., 2018c). The high prevalence of EDs/DE and physiological symptoms of LEA such as oligomenorrhea or FHA in women and low testosterone in men indicates, however, that many athletes are failing to balance energy expenditure with adequate energy intake (Figure 1; Mountjoy et al., 2018; Nattiv et al., 2007).

In athletics, there is a high prevalence of LEA and EDs/DE in middle- and long-distance running and jumping events and is more common in female than male athletes (Table 2; Sundgot-Borgen & Torstveit, 2004). Studies in runners have reported similar or lower daily energy intake compared with nonathlete populations, especially in women (Laughlin & Yen, 1996; Pettersson et al., 1999). A study investigating EA in female and male athletes from a mix of sports reported clinical LEA in 58% of male endurance athletes (n = 22) compared with 51% of female endurance athletes (n = 18) (Koehler et al., 2013). In elite athletics, the prevalence of clinical LEA was 31% and 25% in female and male middle- and long-distance athletes, respectively (Heikura et al., 2018). Among young American collegiate female Division I track and field athletes (19.5 ± 1.8 years), 52% were identified with clinical LEA (Day et al., 2015), while Muia et al. (2016) reported clinical LEA in 18% of adolescent female elite Kenyan runners, compared with 2% among nonathletes. Melin et al. (2015) reported clinical LEA in 20% of elite female distance athletes, and 25% were clinically diagnosed with EDs. These results are consistent with an earlier report by Sundgot-Borgen and Torstveit (2004), who reported a 24% prevalence of EDs in female national team endurance athletes compared with 9% among male endurance athletes. In contrast to running events, literature on the prevalence of LEA with and without EDs/DE in sprint and jumping events is less well characterized (Table 2; Sygo et al., 2018). Sundgot-Borgen and Torstveit (2004) reported a prevalence of EDs in 3% and 6% of male and female national team athletes in sprint and throwing events, respectively. In contrast, the prevalence of EDs in middle- and long-distance running and jumping events were 22% among male athletes and 10% in female athletes. In a study by Hausenblas and McNally (2004) investigating the prevalence of DE in track and field athletes versus nonathletes with higher or lower activity levels, the prevalence was higher in females (14%) compared with males (4%), and in nonathletes with a higher activity level (14%) compared with athletes (7%) and nonathletes (8%) with low activity levels. Discipline-based division showed DE in 12% of the middle- and long-distance runners, 5% of the sprint athletes, and 0% of the field athletes (Hausenblas & McNally, 2004).

While LEA and associated health conditions are observed in adult track and field athletes, there is compelling evidence that LEA with and without DE may start during youth (De Souza et al., 2014; Nattiv et al., 2007). In a study investigating EA in female high school athletes (n = 80) including track athletes (n = 24) and sedentary controls (n = 80), similar prevalence of subclinical LEA among athletes (31%) and controls (39%) was reported (Hoch et al., 2009). Early attitudes on ideal body type and DE have been reported in high school runners. While <2% of the 748 runners surveyed reported DE, over 23% of girls and 8% of boys reported dieting or skipping meals to lose weight (Tenforde et al., 2011). A separate report of a subset of this sample identified the belief that "being thinner leads to faster running performances" in over half of the girls and two thirds of the boys (Tenforde et al., 2015).

Outcomes of LEA

The Relative Energy Deficiency in Sport (RED-S) model describes 10 health outcomes and 10 potential performance effects resulting from LEA in athletes (Mountjoy et al., 2018). A summary of the current knowledge of health and performance impairments related to LEA is reported and discussed in detail in the International Olympic Committee Consensus Statement for RED-S (Mountjoy et al., 2018). In the following section, studies relevant to the reporting of LEA and related conditions in athletics will be presented.

Reproductive Dysfunction

Reduced sex hormones and associated reduced fertility may result from LEA in athletes of both sexes. LEA in female athletes may result in suppressed sex hormones and FHA, a neuroendocrine condition diagnosed by excluding alternative etiology (Gordon et al., 2017). The prevalence of FHA appears to be high in running

Table 2 Physical, Physiological Requirements, Concerns, and Challenges Regarding Energy Availability in the Athletic Disciplines

Discipline	Events	Physique and physiological requirements	Training and competition load	Current evidence, concerns, and challenges
Sprints Hurdles	100 m 200 m 400 m 100/110 m 400 m	Physique requirements: A lean, highly muscular physique. Importance of strong, powerful leg muscles as well as muscular arms. Higher BM and BMI for shorter sprints, somewhat lower body mass and BMI for longer sprints. Usually shorter in stature. Physical/physiological requirements: Focus on optimizing strength, explosive power, and speed.	Training: High volume of strength and plyometric training for power combined with speed and speed endurance training as well as flexibility and technique. Actual work within a single speed/technical session may be only a couple of minutes of duration; therefore, metabolic cost of this type of training may remain quite low. Instead, sprint and resistance exercise may be more intense and lead to ~50–80% depletion of muscle glycogen stores (Slater et al., 2018). Competition: A single race lasts only 10–60 s. However, warm-up, cooldown, and several heats may increase the total duration of work on a competition day/across competition days. In addition, at major championships, some athletes may participate in several events (e.g., 100 m, 200 m, and 4 × 100-m relay), which creates further challenges for performance and recovery within and between competition days. This challenge is similar to that of multisport athletes.	Current evidence: Existing reports show 31% subclinical LEA in track athletes (Hoch et al., 2009), 3–7% EDs in track disciplines (Hausenblas & McNally, 2004; Sundgot-Borgen & Torstveit, 2004), and 23–24% MD (Ikedo et al., 2016). The main challenge: Achieving/maintaining a high level of muscularity, a high power to weight ratio, and optimal adaptation/performance without (a) negative health and performance effects of long-term LEA and (b) unwanted weight gain due to failure to match energy intake to expenditure. The solution: Nutrition should be tailored to maximize training and performance. Periodized approach may be required to support training and performance (high fuel availability around exercise) while minimizing weight gain (low fuel availability and focus on adequate protein intake outside of training; Sygo et al., 2018). During periods of subclinical LEA (Table 1), evenly distributed intake of protein (20–30 g every 3–4 hr) may support the maintenance of FFM and improve satiety (Hector & Phillips, 2018). During "bulking," that is, targeted periods to increase FFM, emphasis should be on moderate-to-high protein and carbohydrate intakes combined with high EA (Table 1).
Jumps	Long jump Triple jump Pole vault High jump	Physique requirements: A high power to weight ratio, and in high jump also leanness. A high level of muscularity is needed in all the disciplines except high jump. Physical/physiological requirements: A combination of superlative speed, power, and explosive strength as well as technical skills is needed in all jumping disciplines.	Training: High volume of sport-specific strength and plyometric training for power combined with speed and speed endurance training, flexibility, and technique. Gymnastics training for pole vaulters. Actual work within a single speed or technical session may be only a couple of minutes in duration; therefore, metabolic cost of this type of training may remain low/modest. Instead, resistance exercise may lead to ~50–80% depletion of muscle glycogen stores (Slater et al., 2018). Competition: A single jump lasts only <10 s. Usually, 3–6 (long jump, triple jump) or up to 10–20 (high jump, pole vault) jumps are performed on a single competition day. Warm-up and cooldown may increase the total duration of work on a competition day. In addition, major championships usually include qualification rounds 1–2 days before the finals. Therefore, performance needs to maintain at high levels across these rounds of competition and provides a challenge similar to sprints and multisport events.	Current evidence: Evidence of 7–22% EDs in field athletes/anti-gravitational disciplines (Hausenblas & McNally, 2004; Sundgot-Borgen & Torstveit, 2004). The main challenges: Achieving/maintaining moderate levels of muscularity, high levels of leanness, and a high power to weight ratio while optimizing adaptation and performance without (a) negative health and performance effects of long-term LEA and (b) unwanted weight gain due to failure to match energy intake to expenditure. Compared with distance runners, jumpers may be less prone to reduced BMD or bone injuries due to the high-impact loading nature of the sport (Tenforde & Fredericson, 2011). The solution: Nutrition should be tailored to maximize training and performance. Periodized approach may be required to support training and performance (high fuel availability around exercise) while minimizing weight gain (low fuel availability and focus on adequate protein intake outside of training) (Sygo et al., 2018). During periods of LEA, evenly distributed intake of protein (20–30 g every 3–4 hr) may support the maintenance of lean body mass and improve satiety (Hector & Phillips, 2018).

(continued)

Table 2 (continued)

Discipline	Events	Physique and physiological requirements	Training and competition load	Current evidence, concerns, and challenges
Throws	Shot put Hammer Discus Javelin	Physique requirements: A high body mass and BMI, moderate muscularity. Strong arms and legs, larger shoulder and hip width. Discus, hammer, and shot put athletes tend to possess higher adiposity than athletes in other athletics events. Javelin throwers tend to have a lower body mass compared with the rest of the throwers to enable a fast run-up before throwing. Physical/physiological requirements: High precision and technical skills. High absolute strength, dynamic power, sense of rhythm, moderate speed, and coordination.	Training: High volume of specific strength training, technique, and skill training. Actual work within a single speed/technical session may be only a couple of minutes of duration; therefore, metabolic cost of this type of training may remain quite low. However, throwers may accumulate thousands of steps/day by retrieving implements, which increases the overall energy expenditure of a throwing session. Resistance exercise is likely to lead to ~50–80% depletion of muscle glycogen stores (Slater et al., 2018). Competition: A single throw lasts <10 s. Usually, 3–6 throws are performed on a single competition day. However, warm-up and cooldown may increase the total duration of work slightly. In addition, major championships usually include qualification rounds a day or two before the finals. Therefore, performance needs to be maintained at high levels across these rounds of competition.	Current evidence: 3–6% of EDs among power athletes (Sundgot-Borgen & Torstveit, 2004). No study has yet investigated LEA in this group of athletes; however, existing evidence of higher-than-average BMD in these athletes may indicate that these athletes are able to maintain optimal EA (Whittington et al., 2009). The main challenges: Achieving/maintaining moderate levels of muscularity and high absolute strength and power levels without unwanted/unhealthy weight gain due to failure to match energy intake to expenditure. The solution: Nutrition should be tailored to maximize training and performance. Periodized approach may be required to support training and performance (high fuel availability around exercise) while minimizing weight gain (low fuel availability and focus on adequate, evenly distributed protein intake outside of training) (Sygo et al., 2019). During "bulking," that is, targeted periods to increase muscle mass, emphasis should be on moderate-to-high protein and carbohydrate intakes combined with high EA (Table 1).
Middle-distance running Long-distance running Race walking	800 m 1,500 m 3,000 m steeplechase 5,000 m 10,000 m Marathon 20 km 50 km	Physique requirements: A lean physique combined with a relatively low body weight. Muscle mass is focused in the lower body while the upper body is usually relatively small in musculature. Middle-distance athletes tend to be somewhat taller than long-distance athletes. Physical/physiological requirements: A high aerobic capacity,[a] power, and speed tend to be more important to middle-distance runners, while economy of movement[b] and efficacy of heat exchange (to avoid overheating) are probably more significant determinants of success in long-distance races.	Training: High volume of aerobic training with high EE especially during the general preparation phase combined with specific training for increasing threshold and running economy during preparation for competition. May involve periods of strength and plyometric training, and targeted altitude and heat training. For middle-distance athletes, training volumes are moderate during the general preparation phase and tend to decrease toward the competition season. Intensity usually remains high throughout and is further emphasized closer to competition season. Long-distance runners and race walkers tend to maintain higher training volumes throughout the year with modest decreases toward the main race. For these athletes, high-intensity training becomes more important closer to the competition season, although the proportion of this type of training remains lower compared with middle-distance athletes.	Current evidence: EDs in 9–24% of adult endurance athletes (Melin et al., 2015; Sundgot-Borgen & Torstveit, 2004). LEA in 18–58% subelite/elite middle-distance athletes (Heikura et al., 2018; Koehler et al., 2013; Melin et al., 2015). MD 60% (Melin et al., 2014; Pollock et al., 2010), lower testosterone in male distance athletes (Hackney & Lane, 2018; Hackney et al., 2017; Heikura et al., 2018), as well as low BMD in 40–45% of athletes (Melin et al., 2015; Pollock et al., 2010; Tam et al., 2018). The main challenges: Athletes are especially prone to develop EDs/DE due to a pressure to obtain and/or maintain a lean, small physique.

(continued)

Table 2 (continued)

Discipline	Events	Physique and physiological requirements	Training and competition load	Current evidence, concerns, and challenges
Middle-distance running Long-distance running Race walking	800 m 1,500 m 3,000 m steeplechase 5,000 m 10,000 m Marathon 20 km 50 km		Training continued: Regardless of racing distance, the energetic demands of training are overall significantly greater than in other track and field events. Competition: Middle distance events last ~2–4 min, while longer distances at the track (~8:30 s to 30 min) and on the road (up to 4 hr) take longer to complete. Therefore, the fuel demands vary significantly between distances (e.g., a high reliance on anaerobic glycolysis in the 1,500 m, while glycogen stores become a limiting factor in the longer road races). Of note are qualification rounds for distances 800 m–5,000 m, which place an additional demand for rapid recovery and optimal performance across competition days. Meanwhile, road races such as the marathon and 50-km race walk demand longer recovery periods where emphasis on adequate nutrition is crucial.	The main challenges continued: Inadvertent (high training loads and/or loss of appetite) or purposeful (targeted weight loss) periods of LEA may lead to negative health and performance effects, including fatigue, poor training quality, and low BMD. Higher risk for reduced BMD compared to athletes in jump events as the lower BM of a distance athlete and the moderate-impact nature of distance running are less efficient to stimulate bone formation (Barrack et al., 2017; Melin et al., 2015; Tenforde et al., 2015). Low BMD may increase the risk for bone stress injury, which impairs training availability. During periods of lower training loads (competition season, taper, illness, or injury), risk of unwanted weight gain if nutrition is not adjusted accordingly. The solution: Nutrition should be tailored to maximize training and performance. Long-distance athletes or those with higher training loads should focus on adequate energy and fuel availability throughout the year, whereas middle-distance athletes or those with lower training loads may benefit from periodizing high fuel availability around special training blocks (high intensity/volume training, altitude training) or sessions (key sessions) while minimizing weight gain by targeted carbohydrate restriction outside of these periods (low-volume training, easy sessions, return from injury) (Burke et al., 2018). In addition, during periods of subclinical LEA (Table 1), evenly distributed intake of protein (20–30 g every 3–4 hr) may support the maintenance of FFM and improve satiety (Hector & Phillips, 2018).
Multievents	Men's decathlon; 100 m 400 m 1,500 m 110-m hurdles Long jump High jump Pole vault Shot put Discus throw Javelin throw Women's heptathlon: 200 m 800 m 100-m hurdles Long jump High jump Shot put Javelin throw	Physique requirements: A lean, moderately muscular physique with powerful legs and arms. In general, a physique that allows the athlete to be competitive in a range of sports (usually resembles that of sprinters/jumpers) is desirable. Physical/physiological requirements: A combination of speed (all events), endurance (distance runs), power (jumps and throws) and explosive strength (jumps) as well as a wide variety of technical skills (especially jumps and throws).	Training: Usually a single session integrates aspects of strength, speed, endurance, and technical training. Therefore, training sessions may be longer in duration and metabolic load compared with other field athletes. A high emphasis on discipline-specific training is required. Competition: Ten (males) or seven (females) events spread across two consecutive days of competition. A single bout of work is usually <10 s (800 m ~2.5 min and 1,500 m ~4 min); however, several rounds are performed for all field events. Competition day is usually long as events are spread across the day. Therefore, overall energy demands may be rather substantial.	Current evidence: No studies have investigated DE or LEA in this group of athletes. Therefore, potential prevalence may be similar to that of sprinters or long/triple jumpers or pole vaulters. The main challenges: The athlete may need to prioritize nutrition/physique goals between events that benefit from leanness and a high power-to-weight ratio (runs and jumps) with risk of LEA, which in the long-term has negative health and performance outcomes. Contrary events where high BM and absolute power are required for successful performance (throws), the main challenge is avoiding unwanted gains in FM. The solution: Nutrition should be tailored to maximize training and performance. Periodized approach may be required to support training and performance (high fuel availability around exercise) while minimizing weight gain (low fuel availability and focus on adequate protein intake outside of training) (Sygo et al., 2019). During periods of subclinical LEA (Table 1), evenly distributed intake of protein (20–30 g every 3–4 hr) may support the maintenance of FFM and improve satiety (Hector & Phillips, 2018).

Note. BM = body mass; BMD = bone mineral density; BMI = body mass index; DE = disordered eating; EA = energy availability; EDs = eating disorders; EE = energy expenditure; FFM = fat-free mass; FM = fat mass; LEA = low energy availability; MD = menstrual dysfunction.

[a]High aerobic capacity: VO_2max; that is, the maximal amount of oxygen that the body is able to utilize for aerobic energy metabolism within the muscles. [b]Economy of movement: that is, the proportion of VO_2max that the athlete is able to sustain for prolonged periods.

events. Self-reported menstrual dysfunction was observed in 60% of English elite middle- and long-distance runners (Pollock et al., 2010) similar to results observed in Swedish and Danish middle- and long-distance athletes with 60% clinically verified FHA (Melin et al., 2015). Among young track and field athletes, 40% reported menstrual dysfunction (Day et al., 2015). In contrast, elite and adolescent sprinters have a reported prevalence of 23–24% self-reported menstrual dysfunction (Ikedo et al., 2016; Sygo et al., 2018). Polycystic ovarian syndrome is common in the general population and phenotypes such as coexistence of FHA and has been reported (Gordon et al., 2017). To ensure correct diagnosis and treatment, a thorough clinical evaluation of the causes of menstrual dysfunction is recommended (Gordon et al., 2017). Health concerns with FHA include impaired bone mineral density (BMD), elevated risk for bone stress injury (BSI), impaired fertility, and increased cardiovascular risk factors (De Souza et al., 2014; Mountjoy et al., 2018; Nattiv et al., 2007).

A recent review concluded that the specific neuroendocrine changes from LEA are not as well understood in male athletes (Elliott-Sale et al., 2018). While the mechanism is inconclusive, male athletes appear to be at risk for lower testosterone levels and associated symptoms of hypogonadal state. A cross-sectional investigation in middle- and long-distance runners and race walkers reported reduced testosterone levels in males with clinical LEA (Heikura et al., 2018). Endurance training intensity and duration are both negatively associated with libido (Hackney et al., 2017), and a 30% reduction in testosterone levels has been reported in athletes with at least 5 years of endurance running compared with athletes with fewer years of training (Hackney & Lane, 2018). The reproductive changes associated with lowered testosterone levels have potential health implications relative to fertility, bone health, and metabolic function in men (Hackney & Lane, 2018).

Impaired Skeletal Health and BSI

Bone mineral density *Z* score <–1.0 has been proposed as low BMD for both female and male athletes participating in land-based sports (Barrack et al., 2017; Mountjoy et al., 2015; Nattiv et al., 2007). Risk factors for low BMD identified in female runners include prolonged distance running, lower BMI, menstrual dysfunction, history of BSI, and lower FFM (Barrack et al., 2017; Tenforde et al., 2015). Similarly, male runners with low BMI believe that being thinner leads to faster running performances, and athletes running greater than 30 miles (48 km) per week are at an elevated risk for impaired skeletal health (Barrack et al., 2017; Tenforde et al., 2015). Compared with other disciplines or healthy controls, distance runners may have lower BMD at lumbar spine but higher BMD at weight-bearing sites (Bennell et al., 1997; Tam et al., 2018). Race differences in BMD values between disciplines are poorly characterized. While individuals of African descent usually have higher average bone mass than whites, one study reported that 40% of adolescent Kenyan runners measured alarmingly low spine (nonweight-bearing site) *Z* scores of <–2.0*SD* (Tam et al., 2018). Studies in adolescent female runners have reported nearly 40% prevalence of low BMD (Barrack et al., 2008) and 43–45% in female distance athletes (Melin et al., 2015; Pollock et al., 2010). In contrast, male decathletes (Maïmoun et al., 2008); throwers (Whittington et al., 2009); and power athletes (sprinters, jumpers, and decathletes) (Bennell et al., 1997) have been reported to have higher BMD than healthy controls.

Bone stress injury, often referred to as stress fractures or stress reactions, are overuse injuries common in athletics. Recovery from BSI may be related to and further complicated by the presence of menstrual dysfunction, EDs/DE, and low BMD referred to as Female Athlete Triad risk factors (Nattiv et al., 2013). In an early study by Marcus et al. (1985) investigating menstrual function and bone health in elite female distance runners and controls, BSI was more frequent in amenorrheic versus eumenorrheic women, and Bennell (1997) reported an annual BSI incidence of 21% in elite track and field athletes; no difference by sex was identified. Additional studies in high school runners support similar incidence of BSI by sex (Tenforde et al., 2013). Among young female Division 1 track and field athletes, 32% reported having a history of one or more stress fractures (Day et al., 2015).

Using the Female Athlete Triad Cumulative Risk Assessment, collegiate runners categorized as having a moderate or high risk of the Triad had 4.0- and 5.7-fold risk for sustaining a BSI compared with athletes categorized as having low risk; a majority of runners in the elevated risk category sustained a BSI within average of 1 year (Tenforde et al., 2017). In a recent study, Heikura et al. (2018) reported on EA status, blood hormone concentrations, bone scans, and BSI history in a group of 24 elite male middle- and long-distance athletes. Despite no differences in BMD, groups with testosterone within the lowest quartile of laboratory reference range and LEA had a 4.5- and 7.5-fold higher frequency of career BSI compared with healthy counterparts, respectively.

Metabolic Alterations

Low energy availability has been associated with decreased resting metabolic rate (RMR) in both female (Melin et al., 2014) and male middle- and long-distance athletes (Thompson et al., 1993) compared with athletes with adequate energy intake. In a clinical study in eumenorrheic women, Loucks and Verdun (1998) showed a 22% reduction in triiodothyronine (T_3) after 5 days with clinical LEA. A cross-sectional investigation in track and field athletes found that menstrual dysfunction in women and lower testosterone levels in men were associated with lower T_3 (Heikura et al., 2018), supporting earlier findings of lowered T_3 levels (Marcus et al., 1985; Melin et al., 2015) and RMR (Melin et al., 2015) in FHA compared with eumenorrheic elite endurance athletes. Although the suspected underlying etiology of lowered RMR and T_3 is LEA (Figure 1), further research is needed.

Other physiological consequences of LEA have been reported. Endothelial dysfunction and an unfavorable lipid profile have been reported in distance runners with FHA (Rickenlund et al., 2005), with a potential negative effect on long-term cardiovascular health. Gastrointestinal problems are commonly reported in endurance athletes, and the association of LEA and gastrointestinal problems has been reported in elite female distance athletes (Melin et al., 2014). The immune system may be altered by LEA, although the scientific evidence is scarce. One study reported more upper respiratory symptoms and lower immunoglobulin-A secretion rates in FHA versus eumenorrheic elite collegiate runners (Shimizu et al., 2012). In a study of female elite athletes in preparation for the 2016 Rio Olympic Games, indication of LEA was the leading variable associated with illnesses (Drew et al., 2017).

Psychological

As previously described, various aspects of psychological well-being and psychological problems such as EDs/DE can precede or be caused by LEA (Figure 1). Screening and addressing LEA and mental health risk among athletes such as perfectionism, athletic identity, compulsive exercise, social or sport specific weight pressure, injuries, or teammates with known EDs/DE are recommended (Hinton & Kubas, 2005; Mountjoy et al., 2018; Turton et al., 2017).

Performance

It has been suggested that long-term LEA could negatively affect sport performance through indirect mechanisms, such as reduced recovery and impairment of optimal muscle mass and function (Mountjoy et al., 2018; Nattiv et al., 2007). Since LEA increases the risk of injury and illness, performance may be impaired due to the loss of training (Drew et al., 2017). Van Heest et al. (2014) reported a 9.8% decline in 400-m swim velocity during a 12-week competitive season in young elite in swimmers with chronic ovarian suppression and metabolic and hormonal perturbation secondary to energy deficiency, in contrast to an 8.2% improvement in eumenorrheic swimmers. Few studies, however, have investigated the impact of LEA on performance, and no studies to date have been performed in primary sport of athletics. A greater power to mass ratio is often regarded as important for running performance (Table 2); however, despite lower body weight and fat mass in elite amenorrheic endurance athletes, Tornberg et al. (2017) found no improved aerobic capacity compared with eumenorrheic athletes. Furthermore, FHA athletes had decreased neuromuscular performance measured as knee muscular strength and endurance and reaction time compared with the eumenorrheic athletes, and lower neuromuscular performance was associated with higher cortisol levels, and lower blood glucose, T_3, estrogen, and FFM in the tested leg. These results suggest that achieving or maintaining a lower body weight through long-term LEA is likely to negatively affect performance and health (Tornberg et al., 2017), a finding supported by results from a study of East African runners (Mooses & Hackney, 2017).

The potential negative effects of LEA and associated conditions on sport performance, and the lack of evidence regarding EA in athletic disciplines such as jumps and sprints, especially in male athletes, clearly indicate the need for more research in this area.

Manipulation of Weight and Body Mass

Similar to the yearly periodization of training, nutrition may need to be periodized to best support adaptation and performance (Stellingwerff, 2018). Although optimal EA is crucial for health and performance, periods of subclinical LEA may be necessary to reach the desired physique goals (Tables 1 and 2). Notably any effort by an athlete to target a specific physique for performance in athletic disciplines needs to account for physiological demands to ensure this does not compromise health and performance (Mountjoy et al., 2018; Tornberg et al., 2017).

Scientific evidence of successful periodization of nutrition and physique in athletics is rare. A recent case study by Stellingwerff (2018) is the first to provide insights into a career-long nutrition and body composition periodization of an Olympic female middle distance runner. For this athlete, optimal EA and weight stability with a slightly higher body weight (~2.1%) and body fat percentage during the general preparation phase compared with the competition season were emphasized. The competition season (May to August) was targeted to reach optimal body composition and race weight and included an individualized time line (6–8 weeks) with moderate caloric restriction (−300 kcal/day) together with adequate protein intake (2.0–2.5 g/kg/day); reduced intake of snacks; energy-dense (sweets, fats); and carbohydrate-rich foods on easy training days. Notable to this case is attainment of optimal physique at peak times without sacrificing long-term hormonal and bone health (Stellingwerff, 2018).

Evidence-based studies are required to understand strategies to achieve a specific physique while maintaining health of the athlete. Available evidence to date is presented, but these studies should be interpreted cautiously when applied to an individual athlete. Studies in leaner athletes (jumpers, sprinters, and middle- and long-distance athletes) suggest a gradual weight loss rate of 0.5–1% per week to preserve FFM (Garthe et al., 2011; Huovinen et al., 2015), sex hormones and reproductive function (Huovinen et al., 2015; Williams et al., 2015), RMR (Trexler et al., 2014), and cortisol (Huovinen et al., 2015). Regardless of event, weight loss should be carefully planned and time limited in the months preceding the competition season, with a diet and training regime provided by professional counseling ensuring subclinical LEA to reduce risk for adverse performance outcomes (Table 2). Weight manipulation among young athletes may delay pubertal development, growth, and bone accrual as well as increase risk of developing EDs/DE (De Souza et al., 2014; Mountjoy et al., 2018; Nattiv et al., 2007). Therefore, body weight manipulation for athletes younger than 18 years should be avoided.

Periodization of EA across days or weeks and within day may be useful weight-loss strategies because periodic increases in EA theoretically counteract adaptive thermogenesis, enabling further weight loss (Trexler et al., 2014), although contrary findings exist (Sundfør et al., 2018). Studies in female and male athletes showed that despite similar daily energy balance or EA, larger within-day energy deficits were associated with suppressed reproductive hormones and menstrual dysfunction (Fahrenholtz et al., 2018), lower RMR, and higher cortisol levels (Fahrenholtz et al., 2018; Torstveit et al., 2018). Therefore, during weight loss, careful timing of energy and fuel availability around training might be a useful strategy to combat metabolic stress associated with inadequate fuel supply to the muscles and the brain.

The macronutrient composition of the diet is important to consider for optimal nutrition support to physiological function and performance. Indeed, low carbohydrate availability has been linked to reduced performance (Burke et al., 2017) and lower levels of luteinizing hormone, T_3, and leptin (Loucks & Thuma, 2003). Therefore, to maintain lean body mass (Hector & Phillips, 2018) and RMR (Trexler et al., 2014) during periods of energy restriction, adequate carbohydrate availability and protein intake (1.6–2.4 g protein/kg/day) should be encouraged.

Clinical Application

Screening

Universal screening is recommended across athletics events especially for those who participate in middle- and long-distance events or jumping events. Regardless of event, the early identification of LEA and associated health issues is essential to guide intervention and prevent long-term secondary health consequences. Therefore, screening is recommended in all athletes who might experience pressure to lose weight or fat mass, are injured, or have teammates with diagnosed EDs/DE (Mountjoy et al., 2018). Although LEA is useful in conceptualizing the development of impairments of physiological function, field assessment or screening of true EA is time-consuming and may be subject to methodological errors associated with assessing energy intake, exercise energy expenditure, and

FFM, even when using the best techniques available to the practitioner. When screening for LEA athletes identified as being at risk due to restricted eating behavior, lowered RMR, stress fractures, reoccurring injuries or illness, self-reported menstrual dysfunction or reduced libido needs a more thorough clinical examination and detailed assessment of EA (Burke et al., 2018c; Mountjoy et al., 2018).

Several tools are available to assist in the screening for RED-S. No screening tool has been specifically designed for the sport of athletics. One of the most practical and commonly utilized tools is the preparticipation examination that can screen athletes for early signs and symptoms of RED-S (Ljungqvist et al., 2009). A more specific screening tool for RED-S which can be incorporated into yearly screening is the LEA in Females Questionnaire (LEAF-Q), which has been developed to identify female athletes at risk for long-term LEA (Melin et al., 2014). The LEAF-Q validated in adult elite female endurance athletes, is constructed to identify physiological symptoms of LEA, and it is recommended to also include a validated DE questionnaire during screening (Melin et al., 2014). In a study combining the LEAF-Q with the Female Athlete Screening Tool (McNulty et al., 2001), 44.1% of long-distance runners were categorized being at risk while 32.0% had DE (Folscher et al., 2015). In addition, the International Olympic Committee developed the RED-S Clinical Assessment Tool to assist clinicians with the screening and return to play of athletes at risk (Mountjoy et al., 2015), although validation of the RED-S Clinical Assessment Tool is required.

Although LEA may occur in the absence of EDs/DE (Melin et al., 2015), LEA may be caused by or further compounded by presence of EDs/DE. In athletics, this may be more common in middle- and long-distance running and jumping events where leanness and/or a low body mass is desirable. An elevated *Drive for Thinness* score on the Eating Disorder Inventory may also be a marker for LEA (Gibbs et al., 2011). In addition, validated screening tools exist for identifying EDs/DE in the athletic population, although these were developed prior to release of the Diagnostic and Statistical Manual-5 (Hinton & Kubas, 2005; McNulty et al., 2001). Underreporting of self-reported eating pathology symptoms is common (Torstveit et al., 2008) and may relate to the stigma around EDs. Therefore, clinical interviews are required in addition to the self-report screening tools to confirm and differentiate the diagnosis (Melin et al., 2015; Sundgot-Borgen & Torstveit, 2004). As athletes with EDs often have psychological comorbidities such as depression, anxiety, and substance abuse (Giel et al., 2016), and excessive or compulsive exercise often plays a causal role in the development of DE (Hinton & Kubas, 2005; Turton et al., 2017), validated screening tools to identify other psychiatric comorbidities can also be considered as appropriate to ensure optimal treatment of the athlete.

Prevention

Prevention of LEA is focused on nonpharmacological strategies to optimize nutrition and EA. Professional nutritional counseling to track and field athletes focusing on optimal energy and nutrient availability to support periodized training, competitions, specific physical requirements and to prevent injury and illness is recommended (Melin et al., 2016; Sygo et al., 2019). Any athlete seeking to intentionally modify body composition including weight loss should be provided with professional counseling, ensuring a time-limited nutritional treatment plan with safe and effective guidelines that ends with reestablishing adequate EA and weight stability (Melin et al., 2016). Injured athletes should be encouraged to maintain optimal EA for optimal rehabilitation (Table 2; Tipton, 2015).

Prevention initiatives also revolve around education programs focusing on athletes, coaches, and other members of the entourage. A survey of International Federations identified a lack of prevention programs on RED-S in 26 out of 28 Olympic International Federations, indicating the need for education of sport leaders and elite team physicians in the health and performance consequences of RED-S (Mountjoy et al., 2018). Although no specific RED-S prevention programs have been developed or evaluated, there are effective prevention programs for EDs in the athlete population. These include peer led (Becker et al., 2012) and school-based initiatives (Martinsen et al., 2014a) suggesting that successful EDs prevention programs should include sectors outside the domain of sport.

Treatment

The reversal of the energy deficit to achieve optimal EA has been shown to be efficacious in reversing the secondary effects of LEA to the hypothalamic–pituitary–gonadal axis and other body systems in female athletes (Cialdella-Kam et al., 2014). Athletes and coaches require education that the resumption of menstrual function occurs over months and improvement in BMD takes longer (Cialdella-Kam et al., 2014). Nutritional intervention should address not only the quantity of energy intake, but also the timing of food intake around exercise and food choices to maximize micro- and macronutrient availability (Melin et al., 2016; Sygo et al., 2019). The treatment often requires a collaborative team approach including a sport medicine physician, a trained sports dietitian, and a sport physiologist experienced in safe body composition management. If EDs/DE is part of the clinical presentation, inclusion of psychologist specialized in EDs/DE in athletes on the treatment team is also required.

The utilization of the combined oral contraceptive pill for the treatment of low BMD is not recommended, as this does not achieve clear goal of reduced stress fracture risk or improved bone health in athletes (Cobb et al., 2007). Importantly, the combined oral contraceptive pill masks FHA and thus may contribute to delayed treatment of LEA. Should the resumption of menstrual function not occur with an adequate trial of nonpharmacological interventions identified above, the use of transdermal estradiol with cyclic oral progestin can be considered (Gordon et al., 2017). The lack of resumption of menses may be an indication of an underlying comorbidity of EDs/DE or represent athlete noncompliance in the treatment program. The use of athlete treatment contracts and removal from sport participation may be required (Mountjoy et al., 2015, 2018).

Athletes presenting with severe EDs who are medically unstable with a cardiac arrhythmia (e.g., bradycardia); electrolyte imbalance; or hypotension should receive intensive in-patient treatment. Modification to the treatment plan may be required to address comorbid psychopathologies associated with EDs (Sansone & Sansone, 2007).

Conclusion

Low energy availability and related clinical conditions are of great concern in athletics, particularly among male and female athletes in middle- and long-distance running and jumping events. However, more studies of the prevalence in sprint, jumping, and multievents are needed. Weight loss may occur in the short-term, but long-term LEA negatively affects both health and performance. Therefore, maintaining optimal EA is important for long-term health and performance, while shorter periods of subclinical EA may be required to reach optimal physique goals, especially close to the competition season. Any effort by an athlete to intentionally manipulate EA to achieve a specific physique for sport requires medical supervision including use of sports dietitian to ensure minimum adverse health outcomes during periods of LEA involving periodizing energy and fuel availability around key training sessions and an adequate protein intake. Screening and education with focus on nutrition to maintain optimal EA are important for early intervention and management.

Novelty and Practical Application Statement

The prevalence of LEA and related clinical conditions is high among male and female middle- and long-distance athletes but also exists in female sprinters with an increased risk of impaired health and performance. Young athletes should be discouraged to manipulate body weight, and sports dietitians counseling adult athletes who need to lose weight should ensure safe and effective weight loss followed by reestablishing optimal EA and weight stability.

Acknowledgments

The manuscript preparation was undertaken by A.K. Melin, I.A. Heikura, A. Tenforde, and M. Mountjoy. All authors approved the final version of the paper. None of the authors has any potential conflicts of interest.

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