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COMMENTARY

Relative Energy Deficiency in Sport in Male Athletes: A Commentary on Its Presentation Among Selected Groups of Male Athletes

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Low energy availability (LEA) is a key element of the Female Athlete Triad. Causes of LEA include failure to match high exercise energy expenditure (unintentional) or pathological behaviors of disordered eating (compulsive) and overzealous weight control programs (misguided but intentional). Recognition of such scenarios in male athletes contributed to the pronouncement of the more inclusive Relative Energy Deficiency in Sport (RED-S) syndrome. This commentary describes the insights and experience of the current group of authors around the apparently heightened risk of LEA in some populations of male athletes: road cyclists, rowers (lightweight and open weight), athletes in combat sports, distance runners, and jockeys. The frequency, duration, and magnitude of the LEA state appear to vary between populations. Common risk factors include cyclical management of challenging body mass and composition targets (including "making weight") and the high energy cost of some training programs or events that is not easily matched by energy intake. However, additional factors such as food insecurity and lack of finances may also contribute to impaired nutrition in some populations. Collectively, these insights substantiate the concept of RED-S in male athletes and suggest that a specific understanding of a sport, subpopulation, or culture may identify a complex series of factors that can contribute to LEA and the type and severity of its outcomes. This commentary provides a perspective on the range of risk factors that should be addressed in future surveys of RED-S in athletic populations and targeted for specific investigation and modification.

Keywords: combat sports, East African distance runners, jockeys, road cyclists, rowers

Recognition of low energy availability (LEA) in male athletes, associated with a range of negative outcomes, played a role in the framing of the Relative Energy Deficiency in Sport (RED-S) syndrome (Mountjoy et al., 2014). Indeed, a variety of scenarios have been investigated in which male athletes report dietary intakes that are unable to meet the energy costs of maintenance of health and well-being, as well as the expenditure associated with their training/event programs (Lombardi et al., 2012; Morton et al., 2010; Wilson et al., 2014a). The initial response to RED-S included criticism of the elevation of these scenarios to the same level of concern or management as afforded the Female Athlete Triad (De Souza et al., 2014). This was based on considerations of both the relative recentness of the investigations among male athletes and suggestions that physiological/biological differences

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between sexes may alter the type and severity of the sequelae of LEA in male populations (De Souza et al., 2014). It is also noted that females across all ages, cultures, and communities are more concerned than their male counterparts about body image and composition and are more likely to exhibit the major risk factor for LEA: a drive to reduce body mass/body fat (Loucks et al., 2011). More recent reviews, however, have confirmed that although LEA in male athletes may involve different or novel issues to those seen among their female counterparts, there is justification for concern and further investigation of the situation in male athlete cohorts (Tenforde et al., 2016). The current state of knowledge of resulting effects of LEA on endocrine changes and health outcomes in male athletes is provided elsewhere (Elliott-Sale et al., 2018).

Typically, the factors underpinning LEA are considered to range from failure to meet the high energy costs of some training/competition programs (unintentional), to overzealous but often well-intentioned behaviors to control body mass or competition (misguided), and to disordered eating/eating disorders (compulsive) (Loucks, 2004; Mountjoy et al., 2014). Nevertheless, a suite of factors within the culture, regulation, and performance drivers of a sport/event may predispose an athlete to adopting eating and/or exercise patterns that result in LEA. The aim of this commentary is to summarize the experience and insights of the current group of authors about the unique risk factors and apparent outcomes of LEA in some specific populations of male athletes. It will explore the characteristics that may contribute systematic or predictable stressors resulting in a mismatch between energy intake and the energy cost of training or competition loads. This is not intended to be a systematic or comprehensive summary of all male athletes who are at risk of LEA or who show symptoms associated with RED-S. Rather, this commentary is an opportunistic account of our lengthy history of sports nutrition research and practice with a specific range of elite male athletes who demonstrate an elevated risk of LEA. Our observations will be integrated with the current literature to summarize the unique issues underpinning LEA as well as the manifestations of RED-S in these populations (see Table 1). This may provoke interest in a more systematic investigation across a larger range of male athletes to identify factors that cause LEA and increase or attenuate its effects on health, function, and performance. A summary of some key areas that should be addressed, at least with the current athlete populations (Table 2), may help to drive these activities and to support a more systematic investigation. Understanding the complexity of the environment in which LEA occurs, both for male and female athletes, may allow strategies to be better targeted for prevention, early detection, and effective management of problems.

RED-S in Male Road Cyclists

Road cyclists may have LEA resulting from the sustained high energy expenditure combined with the challenges of optimizing physique. Road cycling involves high volume training, long seasons with frequent racing (e.g., 60–80 days/year), and competitive events including single races of up to 6–8 hr and stage races such as the Grand Tours (Tour de France, Vuelta a España, and

Table 1 What Is Known About LEA and RED-s in Some Specific Populations of Male Athletes

General male athlete populations (Elliott-Sale et al., 2018; Tenforde et al., 2016)
- Reduced sex hormone testosterone seen in subset of male athletes, particularly in endurance, lean sports or during periods of LEA.
- Impaired skeletal health in male athletes with LEA including running or sports with reduced weight bearing, such as jockeys and cyclists.
- Low body weight may be associated with low BMD particularly in adolescent male athletes.
- Athletes with bone stress injuries in trabecular-rich site may be at higher risk for low BMD.

Cyclists (Barry & Korht, 2008; Campion et al., 2010; Filaire et al., 2007; Yates et al., 2003)
- Combination of high energy demands and impaired energy intake common in longer events, particularly stage races, may result in LEA.
- Dietary behaviors contribute to LEA with goal to achieve high power output to low body mass.
- LEA and DE/ED may contribute to impairments of mood, performance, and recovery.
- Lower BMD particularly noted in lumbar spine of cyclists due to combination of LEA and low weight-bearing activity, including offloading of spine during aerodynamic riding positions.

Combat sports (Brugh et al., 2001; Dolan et al., 2012; Morton et al., 2010; Reale et al., 2018; Rouveix et al., 2007)
- Weight classes of sport may result in dietary and weight loss strategies that contribute to LEA.
- Short periods of weight cycling, a temporary LEA state, may not result in measurable long-term loss in BMD.
- Weight cycling may contribute to cardiovascular disease, endocrine disruptions, and mood disorders.

Jockeys (Dolan et al., 2011; Wilson et al., 2013a, 2013b, 2014a, 2014b, 2015a)
- Requirements for weight making are unique and potentially more extreme than in other "weight-restricted" sports, due to the low and changing weight targets and the low energy expenditure of riding.
- LEA and DE/ED may contribute to low BMD, impaired mood, compromised strength, and impaired riding performance.

Rowers (Jurimae et al., 2003; Slater et al., 2005; Vinther et al., 2008; Woods et al., 2017)
- Lightweight rowers may have greater demands than open weight class to maintain low body weight.
- Demands on lightweight rowers to maintain low weight over time promotes long-term strategies of prolonged LEA.
- Lightweight rowers may be at higher risk for low BMD, rib fractures, and lower testosterone.
- Open weight rowers may experience reduced access to food during prolonged exercise reducing energy intake, high energy expenditure from sport and pressure to optimize power to mass ratio; degree of LEA is likely lower than weight class rowers.

East African distance runners (Fudge et al., 2006; Mooses et al., 2017; Onywera et al., 2004; Tam et al., 2018)
- Chronic LEA state is common from combination of low energy intake combined with prolonged endurance running that often starts during youth.
- Cultural eating practices (e.g., limited dietary range, focus on high-carbohydrate, vegetable-rich foods and sweet beverages) are ingrained, even when away from home environment, and may contribute to inadequate dietary intake.
- Food insecurity, underpinned by lack of finances or sharing of resources with other family members, may also contribute to LEA.
- Resulting LEA may contribute to low BMD in a large portion of runners.

Note. BMD = bone mineral density; LEA = low energy availability; RED-S = Relative Energy Deficiency in Sport; DE/ED = disordered eating/eating disorders.

Table 2 Areas for Further Research on RED-S in Male Athletes

Population	Issue of interest
General populations of male athletes	• Which endocrine systems are affected by LEA? • Are there individual susceptibilities to LEA? • What is the pattern of reduction in biological systems, which accompanies the reduction in EA; is there a threshold of EA below which most problems occur? • What other dietary factors (e.g., carbohydrate availability, vitamin D status, calcium intake) and nondietary factors (e.g., nonweight-bearing activity) contribute/ exacerbate the effect of LEA on bone health and other outcomes, particularly factors that can be manipulated to reduce the effect? • Can sport-specific guidelines for the threshold and duration of LEA that results in health and performance consequences be identified? • What strategies can be employed to correct LEA in athletes for health and performance?
Cyclists	• How do current elite cyclists periodize their body composition and EA over the season? • What is the acute and chronic effect on endocrine systems, metabolic rate, and other issues involved in RED-S? • What is the effect of a riding season on testosterone concentrations, and what are the consequences of low testosterone levels? • How well do elite cyclists manage EA during Grand Tours? • Are there separate effects of competition in Grand Tours or single-day classics on functional outcomes typically associated with LEA? • What is the true prevalence of low BMD among elite male cyclists? How much does LEA contribute to this? • Is there a pattern of LEA (level of energy mismatch and accumulation of period of exposure) that could be considered a threshold for major problems for balance against the benefits provided by low body mass on cycling economy?
East African distance runners	• What is the prevalence of RED-s components/risk factors in elite-level male East African distance runners? • Are there differences in the level of EA that is associated with negative health/performance effects in male and female distance runners from East Africa compared with White population? • Do cultural dietary practices of East African runners (e.g., energy spread, high intakes of fiber and vegetable food sources) contribute to, or protect against, functional outcomes associated with LEA? • How can EA be managed to optimize body mass/composition for running economy and performance while minimizing health effects? • How does chronic exposure to LEA during early childhood affects distance runners health and performance later in their career?
Rowers	• What is the prevalence of LEA in lightweight and open weight rowers, and how much can be attributed to weight management versus inadequate opportunity to meet very high energy expenditure? • What are the health and performance outcomes (bone density, injury, illness, and testosterone) of LEA in rowers? • Do the functional outcomes of LEA in rowers differ in terms of type or severity between weight classes, depending on the underlying cause?
Combat athletes	• What is the typical energy intake, energy expenditure, and EA in specific combat sports? • What combat sports are especially sensitive to symptoms of RED-S? Are there differences between striking and grappling combat sports? • What is the impact of a single training camp and multiple training camps (i.e., making weight several times per year) on symptoms of RED-S, for example, RMR, endocrine and immune function? • How does LEA during making weight affect combat sport-specific performance indices? • Can carefully scheduled periods (e.g., 4–7 days) of “refeeding” and/or reduced “training load” to restore EA during an 8- to 12-week training camp reduce RED-S symptoms while still allowing the athlete to make weight? • How does LEA affect symptoms of RED-S in adolescent combat athletes who also repeatedly make weight? • Do transient periods of LEA during weight cycling (considering a professional boxer may have 40–50 contests) manifest as negative RED-S consequences in retired combat athletes?
Jockeys	• Are the low BMD scores in jockeys indicative of poor bone health or simply representative of a population with extremely low body mass? Following the collection of bone tissue during routine surgery (common with jockeys post fracture), do jockeys with low DXA BMD also present with clinical signs of osteoporosis? • How much are low BMD values in jockeys a consequence of a lack of weight-bearing exercise (and estrogenic stimulus) during adolescence versus poor nutrition? • How dehydrated are jockeys on race day? • Do jockeys display abnormal hormonal profiles on race days? • Does the daily sweating in saunas result in increased sweat calcium excretion, which may contribute to impaired bone health? • Would increasing the minimum riding weights improve the physical and mental health markers in jockeys? • Would daily load-bearing exercise (i.e., skipping) correct or prevent low BMD?

Note. BMD = bone mineral density; LEA = low energy availability; DXA = dual-energy X-ray absorptiometry; RED-S = Relative Energy Deficiency in Sport; RMR = resting metabolic rate; EA = energy availability.

Giro d'Italia) over a 3-week duration (Jeukendrup et al., 2000). Extremely high energy expenditures present an elevated risk of an unintentional energy mismatch from a combination of factors. These include lack of knowledge of nutritional needs; reduced access to energy sources or opportunity to consume them around the long hours spent on the bike; and gastrointestinal challenges, ranging from fatigue-induced loss of appetite to gut distress due to the need to utilize maximal absorptive capacity (Saris et al., 1989). Early studies of the Tour de France reported very high daily energy expenditures (mean: 25.4 MJ; maximum: 32.4 MJ), requiring aggressive (~50% of the daily total) energy intake from carbohydrate-rich drinks and foods consumed while riding (Saris et al., 1989). Nevertheless, most studies of Grand Tour racing typically report surprisingly low body mass losses/apparent energy deficits in these conditions (Jeukendrup et al., 2000; Lombardi et al., 2012; Saris et al., 1989). Indeed, contemporary professional cycling teams appear to have addressed energy availability (EA) challenges during racing via resources such as power meters (monitoring individual energy expenditures) and the involvement of chefs and sports nutrition specialists in the development of personalized race nutrition support. Nevertheless, a study of the Giro d'Italia observed decreases of plasma levels of leptin and cortisol, with increases in adiponectin and markers of bone resorption, suggesting an energy crisis (Lombardi et al., 2012).

In addition to risk for LEA from the exercise demands and nutrition challenges, the culture within road cycling may promote other behaviors aimed at the achievement of extremely low body mass within the peloton. Cyclists may be motivated by the benefits of a high power to mass ratio on cycling performance (Olds et al., 1995), particularly for the hill climbing prowess that often determines race outcomes. Testimonials from the sport's most decorated riders often note that significant weight loss precipitated the dominant phases of their careers (Armstrong, 2000; Boardman, 2000; McMahon, 2016). The phenotype of the successful stage racer/climber is a very low body mass index (BMI < 18 kg/m^2) with extremely low levels of body fat (<35 mm total skinfold fat thickness for seven sites), according to International Society for the Advancement of Kinanthropometry methodology (Marfell-Jones et al., 2012), <10% body fat via dual-energy X-ray absorptiometry assessment of body composition and little upper body musculature (L.M. Burke & J.P. Morton, personal observations, July 2018).

It is possible that some cyclists are genetically predisposed to this physique and achieve it by acceptable methods, such as targeted periods of energy restriction over a short window of the racing calendar during which it is critical to their performance goals (Stellingwerff, 2018). However, unhealthy practices are likely to occur in the achievement of low BMI by at least some male cyclists. Several investigations have reported a high prevalence of restrained eating practices and suboptimal EA from diet/exercise assessments of road cyclists; some have been associated with low bone mineral density (BMD) (Viner et al., 2015), pressure to lose weight (Filaire et al., 2007), and achievement of the diagnostic criteria for eating disorders (Yates et al., 2003). Furthermore, there are numerous anecdotes from lay and social media of highly successful competitors who describe extreme energy restriction, dietary restraint, and disordered eating behavior, often as shared activities. For example, documented practices include the excessive weighing/counting food portion sizes even during high volume training and the postride intake of large quantities of aerated water and pharmaceutical aids, which induce sleep to avoid hunger-associated eating (Hamilton & Coyle, 2012). Such practices are soundly advised against by the current authors on health and safety grounds.

To date, the primary RED-S feature observed in road cyclists is poor bone health. Lower BMD in the lumbar spine is documented in male cyclists compared with other athletes (Rector et al., 2008) and sedentary controls (Campion et al., 2010), and mean losses in BMD of ~1.5% have been reported over a cycling season (Barry & Kohrt, 2008). However, the lower BMD values observations may be explained by additional factors outside LEA. The absence of weight-bearing exercise and the unloading of the spine while riding in an aerodynamic position (Olmedillas et al., 2012) provide poor osteogenic stimuli. In addition, prolonged cycling may result in reductions in serum ionic calcium (Haakonssen et al., 2015) and low carbohydrate availability (De Sousa et al., 2014); these factors also interfere with bone metabolism. However, bone stress fractures do not typically occur among road cyclists to cause the disruptions to training consistency and performance seen among runners and triathletes (J.P. Morton & L.M. Burke, personal observations, July 2018). Rather, traumatic bone fractures are more likely among elite cyclists and are attributed to accidents sustained while riding at high speeds rather than a loss of BMD. Thus, cyclists may not perceive the same concern about bone health as in other endurance sports. Nevertheless, performance may be impaired by factors resulting from LEA including reduced protein synthesis (Areta et al., 2014). The demands of cycling require optimal balance of EA to meet demands of sport while maintaining the health of the athlete.

RED-S in Combat Sports

Combat sports (including boxing, wrestling, judo, taekwondo, and mixed martial arts) are categorized by a series of weight classes intended to promote fair competition by matching opponents of equal stature and body mass (Lanagan-Evans et al., 2011). The failure to achieve the target weight class at a specified time before competition results in withdrawal from competition, with implications for the livelihood of both athlete and coach. Therefore, the ability to "make weight" is considered an art form among combat circles, with athletes usually striving to compete at the lowest weight class possible due to belief this will offer a competitive advantage. Depending on the sport and professional or amateur status, contests take place 4–30 hr after weigh-in. The preceding training camp for each contest may range in duration from 6 to 12 weeks.

Strategies for weight making vary by sport and involve periods of manipulation of body composition with effects on EA, overlaid by rapid loss of body mass via techniques that dehydrate or manipulate gut contents (including fasting, fluid restriction, deliberate sweating, and low residue diets). Each combat sport has a unique culture, an ideal body composition for performance and specific weigh-in regulations that result in different approaches to making weight across sports (Reale et al., 2017a). Indeed, in grappling sports (wrestling, judo, and mixed martial arts), increased reliance on rapid weight loss from dehydration techniques is a common strategy as absolute muscle mass and magnitude of weight regain after weigh-in can offer a competitive advantage (Alderman et al., 2004; Reale et al., 2016). In such circumstances, acute weight losses exceeding 10% of total body mass have been reported within a 24-hr period (Alderman et al., 2004; Crighton et al., 2016). In contrast, the striking sports of boxing and taekwondo, where the magnitude of weight regain is not associated with winning (Daniele et al., 2016; Reale et al., 2018), athletes may use a more gradual reduction in body mass prior to competition involving changes in EA (da Silva Santos et al., 2016). In some situations, muscle mass may be lost by accident throughout the training camp period (Morton et al., 2010); however, other athletes may achieve it intentionally due to the belief it will translate to more rapid and explosive actions. A range of health and performance issues are associated with acute weight-making practices in these sports (Reale et al., 2017b).

In contrast to endurance sports that may cause chronic LEA, short periods of LEA may not result in a loss of BMD. Combat athletes practice transient periods of "weight cycling," two to six times a year, to achieve their perceived "optimal" weight for a specific competition. A case study of a professional boxer assessed daily EA at <5 kcal/kg fat-free mass while he trained three times per day (e.g., fasted morning run, mid-morning boxing-specific session, and an evening track run or strength and condition session). This pattern continued over a 12-week period during which he lost 9.4 kg, which was assessed via dual-energy X-ray absorptiometry to include 3 kg of lean tissue (Morton et al., 2010). However, simultaneous assessment of whole-body bone density showed *Z* scores >2.5. In addition, one study in amateur boxers found greater BMD in hip and lumbar spine when compared with age-matched recreationally active individuals and a cohort of professional jockeys (Dolan et al., 2012). Bone density within normal range was also reported in a population of elite judoists (Prouteau et al., 2006). One possible explanation is that the negative effects of transient periods of weight cycling (i.e., multiple training camps per year) on bone health may be offset by the high osteogenic stimulus of habitual training activities (e.g., professional boxers may run 5–10 km on 5–6 days/week) and typical pattern of rapid weight gain within 7–10 days of postcontest. RED-S may also likely to be more prevalent among professional athletes who are not as closely monitored by the sport science institutes of national governing bodies that support their amateur athletes in preparation for Olympic events (Morton, unpublished data, July 2018).

Although the effects of weight making on bone health may not be as pronounced as other sports with LEA state, other health consequences may result from shorter bouts of LEA. The magnitude and time course of weight loss experienced by combat athletes are often similar to those reported in military personnel during simulated expeditions (Friedl et al., 2000; Nindl et al., 1997) during which severe reductions in testosterone are observed concomitant with hypercholesterolemia and elevated triglycerides. In unpublished observations on professional boxers and mixed martial arts athletes, we previously observed reductions in resting metabolic rate (RMR, ranging from 200 to 350 kcal/day) during the course of an 8-week training camp where absolute testosterone concentrations decreased to <5 nmol/L in the final 3 days prior to competition (Morton, unpublished data). Such fluctuations in hormonal regulation, resting metabolic rate, and potential periods of hyperphagia and binge eating in the weeks after competition (Dulloo, 1997; Dulloo et al., 2017) may also contribute to the enhanced prevalence of obesity among retired weight-cycling athletes when compared with nonweight-cycling athletes and age-matched nonathletic individuals (Saarni et al., 2006). Studies of combat athletes report a high prevalence of disordered eating and eating disorders associated with their weight-making practices (Brugh et al., 2001; Rouveix et al., 2007). Testimonials from combat athletes who exhibit extreme depression and suicidal thoughts upon retirement also cite excessive weight gain as a contributing factor (Hatton, 2013). When taken together, combat athletes appear at risk for LEA and resulting RED-S including cardiovascular disease, endocrine disruptions, and impaired mental health.

RED-S in Jockeys in Horse Racing

The weight-making challenges faced by male jockeys are greater than for any other sport and place them at high risk for chronic LEA state (Wilson et al., 2014b). During the horse racing season, which with the advent of all-weather race tracks now lasts for 52 weeks of the year depending on the region, jockeys may ride in 4–8 race meets/week, with 4–10 rides/day. Indeed, some jockeys have ridden in more than 1,200 rides in a calendar, with weight making required for each race. Jockeys are required to weigh-in before every race, with some needing to meet different targets for each race on the day's program. Unlike other weight-making sports, jockeys are not permitted to fully refuel or rehydrate after the prerace weigh-in, as postrace body mass may be rechecked and must remain within 1 kg of their prerace value (Wilson et al., 2014a). Riding weights are allocated on a handicap basis, with the minimum weight being 49.9–52 kg for flat racing and 57.0–63.5 kg for jump racing (Wilson et al., 2014a). Notably, weight classifications were established hundreds of years ago, without sports science insights, and have not changed significantly over time. As the height of jockeys has continued to increase along with secular trends in the population but weight limits have remained constant, it is now common for jockeys to present on race day with a BMI of <18 kg/m^2 (Wilson et al., 2013b). Management of physique is also made difficult due to the low energy expenditure required for sport. With caloric requirement of race riding being estimated between 50 and 75 kcal/race (Wilson et al., 2012) and a low lean body mass (typically 45 kg), a jockey's total daily energy expenditure may be as low as 2,000 kcal/day (Wilson et al., 2018).

Prior reports suggest that jockeys have tended to rely on peers to obtain weight-making advice (Dolan et al., 2011; Wilson et al., 2013b) and often resort to practices that may compromise health. Common methods to make weight include food restriction, prolonged sweating, and even forced vomiting, known in the horse-racing industry as "flipping" (Dolan et al., 2011; Wilson et al., 2014b). Jockeys typically consume inadequate diets (Dolan et al., 2011; Poon et al., 2018; Wilson et al., 2012, 2013a, 2013b, 2015a) with daily EA as low as <20 kcal/kg lean mass (Wilson et al., 2014a), making them a particularly high risk for RED-S. Total energy intake derived from 7-day food diaries has been reported at <1,500 kcal/day during a typical race-riding week, substantially less than total energy expenditure (Wilson et al., 2013a), with daily carbohydrate intake <3 g/kg body mass. Further analysis of food diaries has suggested that many jockeys only consume one meal per day with the rest of their energy intake coming from convenience snacks. Jockeys present with particularly low vitamin D concentrations (Close et al., 2013) and inadequate intakes of micronutrients, including calcium (Waldron-Lynch et al., 2010). Although these findings are plausible based on the known environment around weight making in the horse racing industry, our knowledge of the prevalence and degree of LEA in jockeys has been largely based on self-reported food diaries, which are known to contain errors of underreporting (Lundy, 2006; Poslusna et al., 2009). Indeed, one study in Irish apprentice jockeys used cameras to record food intake (O'Loughlin et al., 2013) and found significantly higher energy intakes than documented from self-reported food diaries.

Resulting disordered eating behaviors, combined with LEA, have been shown to contribute to a number of RED-S health consequences in jockeys; these include low BMD (Waldron-Lynch et al., 2010; Wilson et al., 2015a), impaired mood profiles (Wilson et al., 2012, 2013a, 2015b), and compromised strength and race-riding performance (Wilson et al., 2014b). Skeletal health may be unnecessarily compromised by the avoidance of weight-bearing exercise by many jockeys, due to their fears that it may increase muscle mass (Martin et al., 2017). Low BMD in this population has been documented (Wilson et al., 2015a) alongside elevated markers of bone resorption and bone turnover compared with healthy controls (Waldron-Lynch et al., 2010; Wilson et al., 2013a). Impaired skeletal health is of particular concern, as jockeys fall from a horse, on average, once per 12 rides (two to three times per week); fractures are common given the speed of movement (>33 km/hr). To date, only one study has reported impaired markers of endocrine function in jockeys (Dolan et al., 2012); here, sex hormone-binding globulin and insulin-like growth factor 1 were increased, and bioavailable testosterone was lower in jockeys compared with controls. It is noted, however, that most blood samples were collected on nonriding days when a jockey is not actively making weight, and this may distort results. Despite limited studies describing endocrine function, eating behaviors, low BMD, and other health issues identified in jockeys suggest that this population is at risk for impaired health resulting from RED-S.

RED-S in Rowers

Lightweight male rowers share challenges and characteristics similar to many weight-category sports that place them at high risk for LEA. A notable difference from other weight division sports is that there are only two weight categories for rowing. In practical terms, this may result in a large number of individuals who are neither big enough to be competitive in open weight events nor small enough to naturally achieve the weight limit for light weight racing. For example, the typical open weight rower (90–95 kg, 190–195 cm; Lundy, unpublished data) has major performance advantages over an 80 kg, 185 cm male rower, due to greater power and strength characteristics, as well as the biomechanical advantages of longer limbs and torso (Kerr et al., 2007; Slater et al., 2005). However, this latter rower is clearly larger than the average weight limit for a lightweight male (70 kg). A large gap is also seen between the typical open weight female rower (75–80 kg, height > 180 cm) and the average weight limit for females of 57 kg (Kerr et al., 2007; Lundy, unpublished data). As there is evidence of a correlation between performance and lean mass among lightweight rowers (Slater et al., 2005), it is understandable that the sport is dominated by athletes who are naturally heavier than their weigh-in target and rely on weight management for competition qualification. Important strategies for managing these athletes include early advice around phenotype suitability to row as a lightweight, as well as ongoing monitoring and support to achieve weight goals in a safe fashion.

Male lightweight rowers have been shown to have lower testosterone (Vinther et al., 2008), lower BMD, and increased risk of rib stress fracture (Vinther et al., 2006) relative to their open weight counterparts, potentially reflecting the imposition of energy restriction associated with weight manipulation strategies. In contrast to the rules and culture of most weight-category sports that promote greater reliance on acute dehydration strategies to temporarily achieve competition weigh-in targets (Reale et al., 2017a), elements of "weight making" in lightweight rowing may favor a more long-term approach to achieving body mass goals through chronic energy restriction. These features include the need to achieve the weigh-in target on each day of competition (up to 5 days in the case of international regattas), which discourages the practice of repetitive dehydration. In addition, some country sports bodies have set up systems of "sliding scale" targets in which rowers can compete "above weight" in prognostic tests or events in the early part of the season while gradually achieving the real weigh-in target important events and international competition. Such practices may assist with a safer approach to avoid rapid weight manipulation. However, lightweight rowers may accumulate longer periods of LEA spanning a season or sporting career, exposing athletes to health consequences from prolonged LEA.

The potential for RED-S in open weight male rowers has only recently been recognized. Indeed, their physique characteristics of large total (~90 kg) and fat-free (~80–85 kg) mass (Lundy, unpublished data) were initially seen as a protective element against LEA, as it signaled a lack of risk for deliberate weight loss activities or disordered eating. However, the training programs of high-level rowers include ~6 hr/day of high energy cost activity for the majority of the year. This may include two rowing sessions, over a total 35–40 km, and a cross training session, of either strength and conditioning or ergometer training. Whereas endurance athletes who undertake similarly high training volumes (e.g., distance runners or cyclists) almost always have low body mass and lean tissue, the energy cost in rowing is elevated by the combination of training load, body size, and muscularity. In addition, the long training hours (the first daily session starting at sunrise and the final session being completed at sunset) can present a practical challenge to achieving sufficient energy intake.

Opportunities for rowers to consume energy and the preferred food choices are necessarily influenced by the time of the sessions, the duration of the break in between, and the type of session to be completed. Training sessions of high intensity also limit the range and volume of food that may be comfortably consumed. The morning session is usually the longest, and athletes may prioritize sleep over digestion time, which can limit the volume of food it is possible to consume presession. Food or drink can be consumed on the water, but only during the short breaks in training, and is further limited in type by the need to avoid contamination with dirt and water in the bottom of the boat. Rowers may manage to meet energy needs in lower training periods but fail to sufficiently increase intake during intensive training blocks with resulting negative metabolic and performance outcomes (Woods et al., 2017). This finding is supported by earlier research suggesting endocrine perturbations in response to intensive training periods (Jurimae et al., 2003; Jurimae, 2003; Vervoorn et al., 1991). Finally, although open weight rowing is not strictly a weight-sensitive sport, many coaches believe that a higher mass within the shell may cause the boat to sit lower in the water and negatively influence the hydrodynamics. Therefore, although it is unlikely to be the most common cause of LEA, a coach's wish to reduce weight/increase power to weight according to the boat class and seating position in the boat may see some male rowers undertaking energy restriction to reduce weight or body fat.

East African Distance Runners

Elite-level East African runners have dominated international running events for decades, with their superior running economy and performance often being attributed, based on limited evidence, to specific anthropometric features and body composition (Mooses & Hackney, 2017). Although very low BMI, body mass, and body fat levels may have a positive effect on running economy, these characteristics are associated with an increased risk of RED-S conditions (Mooses & Hackney, 2017); indeed, East African runners are at high risk for LEA due to combination of high exercise energy expenditure and inadequate energy intake.

The training programs of East African runners are characterized by high total volumes, with large proportion performed at high intensity (Tanser, 1997; Tucker et al., 2015). Chronic exposure to high energy expenditures is common due to a number of factors, including early introduction and consistency of running both as formal training and reliance on running/walking long distances to school during childhood (Onywera et al., 2006; Scott et al., 2003). A striking feature of the dietary studies of East African male distance runners is the apparently low energy intakes, relative to calculated or expected energy expenditures (Onywera et al., 2004; Fudge et al., 2006, 2008). Potential explanations include artifacts due to the well-known limitations of methodologies in these areas (Burke et al., 2018), coincidence with periods of energy deficit/body mass loss, and/or reduced energy expenditure due to metabolic adjustments to LEA. Little is known of the reliability and validity of documentation of dietary and exercise behavior by these cohorts. However, the available literature suggests that there is evidence of different causes of energy discrepancies: for example, in one 7-day training camp, the energy mismatch was associated with weight loss (Onywera et al., 2004); whereas in another involving doubly labeled water estimation of energy expenditure, it was associated with underrecording of intake and variable experiences of weight change/energy balance between subjects (Fudge et al., 2006).

Consideration of factors underpinning energy intake should also include consideration of the commonly consumed foods and eating patterns. Here, there are also striking patterns, which are atypical for the Western diet but share attributes with eating styles of LEA populations and may further contribute to the problematic health outcomes. Dietary surveys of East African distance athletes (Beis et al., 2011; Christensen et al., 2002; Fudge et al., 2006, 2008; Onywera et al., 2004) report a very high contribution of carbohydrate to energy intake (~60–80% energy), high reliance on vegetables (80–90% of diet) rather than animal sources of food (10–20%), and very limited food variety (staple foods: bread, boiled rice, pasta, boiled potatoes, porridge, cabbage, kidney beans, *ugali* maize meal, and *injera* flatbread). Patterns of intake typically include distribution of energy to a small number of meals over the day, regular experience with long exercise sessions undertake in a fasted state, but significant energy intake from sweetened hot beverages (Fudge et al., 2006, 2008; Onywera et al., 2004). Contributors to inadequate energy intakes include cultural eating patterns (e.g., fiber-rich unvaried diet, few eating occasions in a day) and the interaction with high training loads (e.g., lack of intake during training hours, postexercise loss of appetite). The manipulation of body mass and composition for performance also seems to be involved because it has been observed during precompetition training camps (Onywera et al., 2004); and although it is unclear how intentional/deliberate this is, majority of the athletes report their ideal body weight for racing to be lower than that during preparation period (Mooses, unpublished data).

Finally, food insecurity is likely to play a role in contributing to LEA. The pursuit of running success is often undertaken with the intention of creating income for the individual and family (often extended family). There are anecdotal reports that many runners may not be able to afford sufficient food to support their training requirements, and even when success increases the resources of the individual, the athlete will often still skip meal(s) to share their benefits with dependents (Mooses, personal communication with Kenyan runners). In addition, many Kenyan runners continue to follow at least part of their diet customs while living and competing abroad (Fudge et al., 2006; Mooses, personal communication with Kenyan athletes), which they ascribe both to financial reasons as well as their belief that the Kenyan diet might be one of the factor to their superior performance. To this end, it is not surprising that these athletes rarely use any supplements (Beis et al., 2011; Onywera et al., 2004) or sport drinks for energy support around training sessions because they consider them to be very expensive.

Although East African running cohorts remain incompletely described in the traditional considerations of LEA, there is evidence that problems could be reasonably prevalent. Indeed, a new study of adolescent female distance runners from East Africa have reported a significant indication of RED-S symptoms (Muia et al., 2016). Studies of males are even less prevalent. However, a case study of osteoporotic fracture in an elite Kenyan runner (Pollock & Hamilton, 2008) reported BMD *T* score −2.9 in the lumbar spine. Interestingly, blood parameters were all within normal ranges, and self-reported dietary intake may be similar to the other squad members. Preliminary data (Mooses et al., 2017) from a study of RED-S in elite male Kenyan distance runners indicate low lumbar spine BMD (Z score < -1.0) in 30% of participants, whereas Tam et al. (2018) found Z scores below −2.0 in 40% of a different cohort. Of course, the complication of comparing BMD between different ethnic groups is noted, particularly populations in which nutritional status in early life may be compromised is noted. The findings in African runners of impaired bone health have been seen in other populations of runners in North America, including adolescent female and male runners (Barrack et al., 2008, 2017; Tenforde et al., 2015) and college-age runners (Kelsey et al., 2007; Fredericson et al., 2007; Tenforde et al., 2018). This worrying evidence about bone health of East African runners warrants further investigation of the prevalence and cause of LEA, as well as hormonal and functional measures of the components of RED-S and their effect on elite-level endurance performance (Mooses et al., 2017).

Reflections

Insights from the current authors and additional literature evidence support the concept that RED-S occurs in male athletes across multiple sports. LEA results from a mismatch between energy intake and the energy expenditure, and the factors contributing the level and duration of exposure to LEA are often unique to the sport. Some of these factors may be inextricably linked with optimal performance, such that the athlete walks a tightrope between harm and benefit. However, others may be extraneous or coincidental and may be more easily manipulated once they are identified. Importantly, this commentary shows the importance of understanding the characteristics of a sport or athletic group that might predispose a male athlete to LEA and/or affect their risk of developing various components associated with RED-S. For example, although weight-category events are identified as high-risk sports due to the general culture of acute and chronic manipulation of body mass, we identified differences in the typical patterns of exposure to LEA between jockeys, lightweight rowers, and combat sport participants, as well as differences in the manifestation of outcomes, such as low BMD and low testosterone concentrations. Indeed, even within combat sports, there are subtle differences that can be explained by variations in behavior based on cultural beliefs or practices deemed to enhance event-specific performance. Similarly, consideration of the special issues present in East African distance running populations is important if the evolving research continues to identify them as cohort at risk of RED-S. Even if this research finds that the prevalence and severity of issues (e.g., low

BMD) are similar to that found in the more established literature on North American White populations, it seems likely that different factors will contribute to these problems (e.g., food insecurity, differences in the hierarchical value placed on Western concepts of sports nutrition and culturally derived patterns of food choice and distribution over the day). Therefore, different solutions to prevention and management of the problem are needed.

Future research should investigate both the factors that contribute to an energy mismatch in male athletes, as well as the effects of LEA on their health and performance. Table 2 provides a summary of key questions that should be addressed in the current populations of male athletes as well as others who may be exposed to individual- and sports-specific risk factors.

Conclusion

In summary, systematic research addressing the prevalence and causes of LEA, and strategies to improve health outcomes of male athletes suffering from RED-S should be a high priority for the sports medicine community. Although the issues may be different in males to those of their female counterparts, there is mounting evidence that RED-S is prevalent and problematic in a range of sports. The insights gained from this commentary (summarized in Tables 1 and 2) include the importance of understanding the unique and specific factors that occur within sports, events and subpopulations, as well as the need to strategically target information on how the outcomes affect athlete health and performance.

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