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REVIEW ARTICLE

Parallels with the Female Athlete Triad in Male Athletes

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Abstract Participation in sports offers many health benefits to athletes of both sexes. However, subsets of both female and male athletes are at increased risk of impaired bone health and bone stress injuries. The Female Athlete Triad (Triad) is defined as the interrelationship of low energy availability (with or without disordered eating), menstrual dysfunction, and low bone mineral density. The Triad may result in health consequences, including bone stress injuries. Our review presents evidence that an analogous process may occur in male athletes. Our review of the available literature indicates that a subset of male athletes may experience adverse health issues that parallel those associated with the Triad, including low energy availability (with or without disordered eating), hypogonadotropic hypogonadism, and low bone mineral density. Consequently, male athletes may be predisposed to developing bone stress injuries, and these injuries can be the first presenting feature of associated Triad conditions. We discuss the evidence for impaired nutrition, hormonal dysfunction, and low bone mineral density in a subset of male athletes, and how these health issues may parallel those of the Triad. With further research into the mechanisms and outcomes of these health concerns in active and athletic men, evidence-based guidelines can be developed that result in best practice.

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Key Points

A subset of male athletes, especially those participating in sports emphasizing leanness, may exhibit deficits in nutrition, reduction in sex hormones, and/or impaired bone health.

Although more research is needed, this pattern of medical conditions seen in the male athlete appears analogous to that of the Female Athlete Triad.

By describing the current knowledge regarding features of the Female Athlete Triad in male athletes, we identify topics for future research to advance the health of male athletes.

1 Introduction

Sports participation offers many health benefits to both male and female athletes. However, a subset of individuals may experience adverse health consequences associated with sports participation, including impaired bone health. The Female Athlete Triad (Triad) describes risk factors for low bone mineral density (BMD) in girls and women, and our understanding has emerged over the past 2 decades. Our understanding of the Triad has evolved from the original definition outlined in 1993 as a syndrome of three

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interrelated conditions: disordered eating (DE), amenorrhea, and osteoporosis [1]. The most recent American College of Sports Medicine position paper on the Triad recognizes it as a syndrome of three interrelated conditions that includes low energy availability (with or without DE), menstrual dysfunction, and low BMD, with each component of the Triad existing on a spectrum ranging from health to disease [2]. The 2014 Female Athlete Triad Coalition consensus statement recently expanded upon the 2007 position paper by providing clinical guidance on the management and treatment of the Triad using the scientific evidence available to date [3]. The consensus statement also highlights the importance of screening and prevention given the known prevalence of each component of the Triad and longitudinal evidence that these health issues, including impaired bone health, may be irreversible, especially if not addressed early [3, 4].

While the Triad has been researched and characterized extensively, particularly among collegiate and young adult athletes, male athletes may also experience similar conditions, although the characteristics, prevalence, and clinical significance are largely unknown. Male athletes participating in sports emphasizing leanness who present with bone stress injuries may also exhibit concurrent nutritional, endocrine, and/or bone health concerns similar to those of women with the Triad. In some of these cases, male athletes are found to have inadequate nutrition, hypogonadotropic hypogonadism, and/or impaired bone health, including bone stress injuries [5–7]. While several case studies have reported this pattern, few investigations have characterized this condition in the larger population of male athletes. Evidence from original research studies has suggested hypogonadotropic hypogonadism replaces the functional hypothalamic amenorrhea component described in the Triad [8].

In clinical practice, a subset of male athletes, similar to female athletes, presents with bone stress injuries and may have a combination of low energy availability, hypogonadotropic hypogonadism, and low BMD. We propose male athletes may have one or more components, and, similar to the Triad, each falls on a continuum from health to disease [2]. Therefore, the purpose of this review is to provide an overview of current evidence regarding the influence of nutrition and hormones on bone health in male athletes. We also identify gaps in the current literature that limit our understanding of these conditions in male athletes and propose directions for future research.

2 Methodology

A review using PubMed was initially completed in May 2014 and included the following search terms: male, athlete, hypogonadism, and/or energy availability. We identified additional articles by cross-referencing them from our initial search.

Males may have one or more of these conditions, although the prevalence of each condition may be less common than in female athletes [9].

3 Low Energy Availability, Eating Disorders, Disordered Eating

As recognized in the 2007 American College of Sports Medicine female athlete triad position paper, low energy availability and nutrient deficits may be intentional, due to dieting and/or DE behaviors, or inadvertent, resulting from a lack of knowledge regarding the amount and type of foods that should be eaten to support an athlete's training and subsequent exercise energy expenditure [2]. Identifying the nutritional status of athletes and their risk of undernutrition is key, as prior studies in women have documented a dose–response relationship between energy availability for metabolic, reproductive, and growth hormones and biomarkers of bone metabolism [10]. Thus, under-eating may contribute to both nutrient deficits and physiological consequences that may hinder performance and health.

While it cannot be assumed that DE behaviors (i.e., dietary restraint) and pathologic behaviors (i.e., excessive exercise, use of laxatives or diuretics, self-induced vomiting) necessarily contribute to energy and nutrient deficits, several reports evaluating DE status and dietary intake confirm lower reported energy intakes among athletes with DE in both sexes [11, 12]. Limited reports in men, similar to those in women, identify a higher prevalence of DE behaviors and nutrient deficits among athletes than among non-athletes, especially in sports emphasizing leanness [13, 14].

3.1 Low Energy Availability

The term 'energy availability' has been previously used to describe the difference between energy intake and estimated energy expenditure, standardized to kilogram of fat-free mass (FFM) [9]. The concept of adequate energy availability is under-studied in male athletes, although nutritional deficits have been identified in a subset of athletes. To our knowledge, the largest nutritional study to date spanned 8 years and evaluated the diet and nutritional adequacy of the diets using 4- to 7-day food logs among 419 elite male and female Dutch athletes competing in endurance, strength, and team sports [15]. The authors concluded that a majority of athletes in all sports consumed inadequate levels of carbohydrate, and athletes of both sexes participating in sports emphasizing leanness were observed to exhibit dieting and under-eating throughout the year. This study was published in 1989 and has yet to be updated. However, smaller-scale studies also inform us of the risk of energy and nutrient deficits in male athletes.

Investigations among male adolescent athletes competing in ball or team sports, such as football, soccer, and ice hockey, indicate sufficient absolute (kcal) and relative (kcal/kg) energy intake, ranging from ~40 to 60 kcal/kg [16–19]. In contrast, athletes in sports emphasizing leanness or requiring weight-control behaviors (wrestling, judo, horse-racing) have been observed to have periods of low caloric intake or other nutritional deficiencies [11, 20, 21]. Similar to weight class and aesthetic sports, several studies have identified similar deficits in male endurance athletes. One report evaluating 37 male adolescent cyclists and controls found that, despite cyclists exercising fivefold more hours per week than controls, their energy intake (~2300 kcal/day) did not significantly exceed that of control subjects and appeared to fall below recommended intake levels based on their level of training [22]. Additionally, intake of calcium, vitamin D, iron, and B vitamins were below recommendations for both cyclists and controls [22]. Another study among 61 male cyclists demonstrated that the cyclist population had elevated DE behaviors compared with age-matched controls and exhibited poor intake of each food group compared with recommendations [23]. One of few reports in male high school athletes found endurance runners consumed fewer snacks per day than athletes participating in a ball or team sport [24]. Separate investigations in male runners and cyclists identified low caloric intake in athletes, although food and fluid intake surrounding and during competition largely met recommended levels in most reports [25–27]. Performance in and completion of the endurance events was associated with meeting the dietary intake needs [25–27]. These studies suggest sports emphasizing leanness, especially endurance sports, and those sports requiring weight control carry an increased risk of nutritional deficits. Further studies are recommended to clarify estimates of inadvertent versus intentional (i.e., due to DE) deficits, risk factors of undernutrition, mechanisms that may lead to negative effects on bone metabolism and bone health, as well as preventive and educational measures.

3.2 Eating Disorders and Disordered Eating

Sundgot-Borgen and Torstveit [13] evaluated the prevalence of eating disorders (EDs) in athletes in the largest epidemiological study to date. Investigators sampled 1316 elite Norwegian male and female athletes and non-athlete controls, and reported an 8 % prevalence of EDs, including anorexia nervosa, bulimia nervosa, ED not otherwise specified, and anorexia athletica, among the 687 athletes compared with a 0.5 % prevalence among the 629 non-athlete controls. Additionally, a higher prevalence of EDs was detected in the men participating in sports emphasizing leanness (12.9 %), including aesthetic, endurance, weight class, and anti-gravitation sports, than in athletes participating in non-leanness (4.6 %) sports, including technical, ball game, power, and motor sports [13]. These findings convey an approximately 25 times (12.9 vs. 0.5 %) higher prevalence of ED in male athletes in leanness sports than in the non-athlete general population, similar to findings regarding female athletes [13]. Separate investigations in collegiate athletes found symptoms of ED/DE in a subset of the population, although no EDs were reported [14, 28, 29].

Smaller studies, exclusively among athletes participating in sports emphasizing leanness, including endurance, aesthetic, weight class, and anti-gravitational sports, provide additional information on the higher frequency of DE behaviors among this population. In weight class sports, wrestling is notorious for extreme weight-cutting techniques, with reports of the incidence of laxative use, self-induced vomiting, and excessive exercise ranging from 3 to 78 % [30, 31]. In a recent meta-analysis, Chapman and Woodman [32] found that, compared with all other leanness sport types (i.e., aesthetic, endurance, all mass-dependent sports), only wrestling exhibited a significantly higher incidence of DE among athletes compared with non-athlete control subjects. Various studies reported frequent DE behaviors in horse jockeys, a population with weight-control pressures associated with their sport. Dolan et al. [11] found that 71–86 % of a sample of 21 professional jockeys used extreme weight-loss measures, including saunas, dieting, and excessive exercise, to lose approximately 2 kg 1–2 days prior to a race. Moore et al. [33] reported on behaviors of 116 jockeys (91 males) and found that 60 % practiced extreme weight-loss behaviors prior to race day, with the most common behaviors including skipping meals (75 %), sauna use (41 %), and taking diuretics (39 %). Prior studies exhibited a higher incidence of dietary restraint and cognitive control of eating [34] and subclinical eating disorders (~8 %) [35] in male lightweight rowers. Athletes in judo also exhibited increased DE and pathologic behaviors; however, few studies exclusively characterized males [36]. Together, these reports highlight the elevated DE risk profile among male athletes participating in weight-class sports. However, future research is needed to confirm whether these behaviors contribute to chronic energy deficits and subsequent outcomes similar to those of the Triad in male athletes.

Investigations among sport types demonstrated that athletes who participate in sports emphasizing leanness, including endurance sports (cycling and running), appear to have a greater prevalence of DE. Among a sample of 61 male cyclists and 63 male non-cyclists, cyclists exhibited a significantly higher overall score on the Eating Attitudes Test (EAT)-26 (indicating more DE), and a higher score on the dieting and binge eating EAT-26 sub-factors [23]. Additionally, 20 % were classified with elevated DE (EAT-26 score >20) and 8 % reported currently having an ED [23]. Ferrand and Brunet [37] evaluated a sample of 42 elite male cyclists and found that over 57 % had an EAT-26 score >20. Among a sample of male cyclists, Filaire et al. [38] found that 67 % were not satisfied with their weight, 41 % dieted to lose weight, and others reported laxative use and increased exercise for weight-control purposes. While numerous studies reported elevated DE behaviors among female endurance runners, few studies investigated male runners. Tenforde et al. [39] evaluated 306 male high school runners and found that 9 % had previously dieted or skipped meals for the purpose of losing weight. Wheeler et al. [40] evaluated 49 male adult runners and 18 controls and reported significantly higher scores on the EAT in runners than in controls. DiGioacchino DeBate et al. [41] evaluated 583 male and female triathletes and reported elevated body dissatisfaction, extreme restriction of calories and food groups, and excessive exercise for the purpose of weight loss among athletes of both sexes. While further research is needed, these studies suggest an elevated risk of DE among male endurance athletes than in other sport types.

Sundgot-Borgen and Torstveit [13] reported that, among Norwegian athletes, the highest (22 %) prevalence of EDs was in those participating in anti-gravitational sports, including high jump, long jump, triple jump, pole vaulting, and ski jumping. However, a recent study in Brazil reported that, among a combined sample of 156 weight-class, leanness, endurance, anti-gravitational, and aesthetic sport athletes, 43 (28 %) met the criteria for DE using the EAT-26 or the Bulimic Investigatory Test [42]. No significant differences were found between sport type, suggesting athletes in sports emphasizing leanness may exhibit an elevated prevalence of DE.

4 Hypogonadotropic Hypogonadism

Female athletes may develop functional hypothalamic amenorrhea as a consequence of low energy availability [2]. Menstrual dysfunction (oligomenorrhea or amenorrhea) can be easy to identify; however, other women develop luteal-phase defects and anovulation based on the magnitude of energy deficit [43], and these features can be difficult to detect. Similarly, evaluating changes to the male reproductive function requires sophisticated techniques and may complicate the identification of a similar syndrome in males. Clinical symptoms of male reproductive dysfunction are few, and evaluation may require sperm and fertility analysis [44]. Previous research studies identified measurable changes in hormones that influence metabolism and reproduction, such as those of the hypothalamic-pituitary-gonadal (HPG) axis, in male athletes [45–47]. Alterations in these hormones may result from low energy availability occurring, for example, as a result of marked increases in endurance training without an accompanying increased caloric intake. However, few prior studies have evaluated dietary intake and endocrine function [48].

Male endurance athletes in sports emphasizing leanness, including cycling and running, have been shown to exhibit lower levels of reproductive hormones, including testosterone [45–51]. Hackney et al. [52] reported significantly lower serum levels of testosterone among 53 endurance athletes compared with 35 sedentary men. Four of five investigations performed in small populations of endurance runners ($N = 5$–11 per study) participating in high-volume training (≥100 km/week) reported 10–30 % lower levels of total testosterone compared with sedentary controls [46, 49, 53–55]. In contrast, two of six studies evaluating runners with average training volumes less than 100 km/week ($N = 6$–20 per investigation) identified significantly lower testosterone levels in runners compared with sedentary or less active controls [45, 54, 56–59]. De Souza and Miller [44] proposed a "volume threshold hypothesis" to explain findings of altered reproductive function in endurance runners exceeding 100 km/week.

Prospective studies in male runners further demonstrated reductions in testosterone levels [47, 50, 60]. Roberts et al. [47] investigated elite endurance-trained runners taking part in an overtraining protocol consisting of twice the average weekly mileage volume. The authors observed a 40 % reduction in testosterone and a 43 % reduction in sperm counts measured immediately after overtraining compared with baseline values, although testosterone levels returned to baseline values 3 months after resuming normal training. Wheeler et al. [50] studied 15 previously sedentary males who ran up to 56 km/week over a 6-month training period; they reported a subsequent decrease in body weight and testosterone levels. In a separate investigation, Wheeler et al. [40] demonstrated a graded inverse relationship between running mileage and total testosterone levels. Griffith et al. [60] found that testosterone levels in endurance athletes training 1–2 h per day, 6–7 days per week, declined by 12 %. In each of these studies, while testosterone levels declined, the values remained within normal physiological levels. Additional investigations in male athletes identified that testosterone levels were at the lower limits of normal or were reduced compared with age-matched controls in male lightweight rowers [61], triathletes [62], and cyclists [63].

In addition to suppression of serum testosterone, additional studies have suggested that men engaging in high-volume endurance training exhibit other endocrine changes suggestive of central involvement of the HPG axis [44, 51]. Hackney et al. proposed that a subset of males participating in endurance sports may experience changes in the hypothalamic-pituitary-testicular axis that result in lower testosterone levels [8, 46, 64, 65]. However, our current understanding of the precise mechanisms of disruptions to the neuroendocrine axis in male athletes is limited, as investigations in men have been of cross-sectional design or limited to short prospective evaluations of differences primarily in luteinizing hormone (LH) and follicle-stimulating hormone (FSH) with endurance athletes compared with non-athlete controls. A study among six elite male marathon runners training 125–200 km/week found a significantly lower LH pulse amplitude and pulse frequency than in healthy controls [53]. McColl et al. [45] evaluated six male endurance runners training at least 80 km/week and found a reduction in LH total area under the curve but no disruption to LH pulse frequency or amplitude compared with resting values in runners. Similarly, a sample of eight previously recreational athletes taking part in a 2-week training period involving participation in at least four exhaustive exercise sessions on a cycle ergometer per week exhibited significantly lower LH and FSH concentrations after the 2-week period compared with within-subject baseline concentrations and compared with matched controls [66]. However, Wheeler et al. [50] did not detect a significant reduction in LH or FSH in their prospective study in the previously sedentary men participating in 6 months of training. These investigations in male endurance athletes collectively suggest alterations in the HPG axis, and this could be further extrapolated to explain the lower testosterone levels noted in a subset of male athletes. However, future investigations that prospectively identify changes in hormones, including LH and FSH pulsatility and amplitude, would be helpful to understand whether men have processes that parallel those of women in response to changes in energy deficiency.

Research has outlined a dose–response relationship between energy availability and markers of HPG function, including reductions in LH pulse frequency and serum concentrations of estradiol, with increasing levels of energy deficit in women [10, 67]. No similar studies have been conducted in men, although prior research in male endurance athletes suggested a link between factors contributing to an energy deficit, i.e., high-volume training or rapid increases in training resulting in suppression of HPG function [44, 48, 54]. Gomez-Merino et al. [48] reported on the energy status and endocrine function of a sample of 26 male soldiers who underwent combat training consisting of 3 weeks of physical training and a 5-day combat course. The 5-day combat course resulted in an estimated energy deficit of 1800 kcal/day, a subsequent decrease in mean testosterone levels from 15.1 to 9.8 nmol/L pre-physical training to post-combat course, and a 67 % average reduction in serum leptin. Additionally, insulin was reduced, while both norepinephrine and dopamine were elevated, at the conclusion of the combat course compared with baseline values. This study is one of the few reporting on both nutritional status and endocrine function in men and links energy deficiency to reduced testosterone concentrations. Interestingly, the soldiers also concurrently exhibited a significant 67 % reduction in serum leptin concentrations [48]. The reduction in leptin observed in men parallels findings in women consuming a diet yielding a low energy availability of 10 kcal/kgFFM/day [68]. Chan et al. [69] demonstrated that recombinant leptin administered during an acute fast in men preserved the HPG axis function, including normal LH pulsatility and testosterone concentrations, supporting the role of leptin in states of low energy availability. This is notable, as circulating leptin may serve as a signal of energy insufficiency to the brain at the level of the hypothalamus, influencing the adaptations of the HP thyroid, growth, gonadal, and adrenal hormone axes during a period of energy deficit [70].

One recent investigation evaluated changes in metabolic markers, including insulin-like growth factor (IGF)-1 and triiodothyronine (T3), and bone turnover markers in two states of energy availability within men [71]. A total of 11 men completed two trials in a randomized cross-over design study evaluating changes in markers of metabolism and bone over 5 days of restricted (30 kcal/kgFFM/day) and control conditions of energy availability (45 kcal/kgFFM/day). Investigators were not able to detect differences between restricted or control conditions in bone turnover or metabolic markers. Although this was a preliminary study, the findings may suggest that more restrictive thresholds of low energy availability may be necessary to exert changes in endocrine function and bone metabolism in men compared with the thresholds observed in women.

Further research is recommended, including prospective studies evaluating both energy status and endocrine function to identify factors contributing to the decline in testosterone and HPG axis function in male athletes, to understand the similarities between male athletes and the Triad.

5 Low Bone Mineral Density

As with women, men must accrue and maintain peak bone mass to optimize bone strength and resistance to fracture. Several factors influence bone metabolism. Genetics is the strongest factor, although behavioral and environmental influences, such as diet and exercise, also play a significant role [2]. Due to the osteogenic effect of loading forces exerted to bone during exercise, participation in sports that involve high-impact and multidirectional loading activities promotes increased bone mineralization during development, and athletes typically exhibit higher than normal levels of bone mass than non-athletes [72, 73]. However, many men and women participating in endurance sports, including running, do not exhibit above-average levels of bone mass and may even present with 'low BMD' as defined by the American College of Sports Medicine in physically active and athletic premenopausal women and children: BMD or bone mineral content (BMC) Z-score less than −1.0 [2], particularly in sites high in trabecular content [74–76]. The International Society of Clinical Densitometry (ISCD) defined low BMD in male and female children and adolescents (aged 5–19 years) as a BMD Z-score of −2.0 or less [77]. Definitions for osteoporosis in children and adolescents (aged 5–19 years) according to the ISCD include BMD Z-scores of −2.0 or less plus the presence of fractures, and cannot be defined based on Z-scores alone [77]. Z-scores are also used in men aged less than 50 years, and definitions for osteoporosis must include the presence of risk factors as well as low BMD Z-scores [77]. Key behavioral and environmental factors contributing to differences in bone mass among male athletes include differences in loading type during exercise, diet, and endocrine factors.

The type of loading exerted to bone is an important determinant of bone mass and strength [73]. Wolff's law describes how bone responds and adapts to various physiological stressors [78], including ground reaction forces applied to bone during exercise. Athletes participating in sports that promote high-impact and multidirectional loading to bone, such as basketball, soccer, volleyball, and martial arts, exhibit higher BMDs than athletes in endurance activities involving repetitive, lower impact loads, such as long-distance running, or non-impact activities such as swimming or cycling [24, 73, 74, 79, 80]. The timing of loading exposure to bone may also play a role in men, particularly during the second decade of life, during which BMC approximately doubles. Most men reach their highest bone mass by the age of 20 years [81], with peak accrual rates occurring between the ages of 13–15 years. As a result, some investigators recommend participation in ball sports or other high-impact multidirectional loading activities for at least 2 years during early adolescence, particularly at the time of or surrounding the years of peak accrual, to optimize bone mineral gains and prevent future stress fractures [82–84].

Previous studies reported low bone mass or osteoporosis among male athletes who participate in sports emphasizing leanness or activities exerting low-impact loading forces to bone. Dolan et al. [85] reported that male jockeys have lower BMD than boxers and hypothesized this may result from low energy availability from weight-restriction behaviors. Fredericson et al. [74] evaluated bone health in male soccer players, runners, and sedentary controls and found the regional BMDs of male soccer players was superior to that of all groups, with runners showing superior BMD at the calcaneus compared with controls. Tenforde et al. [86] reported that a subset of adolescent male runners (9 of 42) had a Z-score of −1 or less, with two risk factors associated with greater risk for low bone density values that investigators postulated may reflect DE and/or low energy availability: 1) the belief that being thinner leads to faster performances; and 2) body mass index (BMI) $\leq$17.5 kg/m^2. In a separate investigation in collegiate runners, lower BMI was associated with increased risk for bone stress injuries, particularly in men [87]. Impaired lumbar spine BMD values observed in male runners by Fredericson et al. [74] have been reported by other investigators [76, 88]. Male cyclists, who engage in a non-weight-bearing sport that emphasizes leanness, were observed to have similar deficits in BMD, particularly in the lumbar spine [89–91]. Nattiv et al. [92], in their prospective analysis of risk factors for bone stress injuries in collegiate runners, found that male and female runners with a higher percentage of bone stress injuries in trabecular regions (femoral neck, pubic bone, and sacrum) compared with cortical sites, were distance runners and had significantly lower BMD in both lumbar spine and total hip [92].

Although a representative prevalence of low BMD in male athletics is unknown, current research suggests that the subset of athletes with the highest prevalence of impaired bone health appears to be those participating in endurance and weight-class sports. If a cut-off for low BMD of a Z-score or T-score less than –1.0 is used, 19–40 % of elite collegiate and post-collegiate male runners [74, 76, 86] and 25–89 % of competitive and master male cyclists [89, 90] are below this threshold. We caution that the studies in the male athlete population to date cannot be used to report a true prevalence of low BMD or osteoporosis, as investigations are limited by small sample sizes, athletes being evaluated at different ages, and few studies publishing the proportion of athletes meeting threshold cut-off for low BMD, limiting the generalizability to the overall population of athletes. Additionally, investigators in most studies reported T-score values using thresholds of –1 and –2.5. Current published guidelines recommend the use of Z-scores when evaluating bone health in athletes [2, 77]. Whether a Z-score cut-off of –1 should be applied to define low BMD in male athletes is currently unknown due to the limited number of studies in this population. However, the proportion of athletes with low BMD Z-scores and T-scores over normal controls within studies suggests that a portion of male athletes participating in sports emphasizing leanness, particularly endurance sports, may be at increased risk for impaired bone health.

As outlined earlier, factors related to low energy availability and disruptions of endocrine function may also influence bone in male athletes. Though the effects are not characterized in experimental studies to the extent to which they have been in women, male athletes participating in sports emphasizing leanness may be at risk for low BMD. Changes in metabolic and reproductive hormones, including estradiol, contributes to impaired bone health seen in female athletes with the Triad [2, 10]. Similarly, reduced testosterone and other sex hormones associated with sports participation may account for observed lower BMD [51, 75, 93]. In their cross-sectional study of 26 male collegiate athletes, Ackerman et al. [93] identified that concentrations of free and total estradiol were more predictive than free or total testosterone for influencing bone density in male collegiate runners and wrestlers [93]. One cross-sectional investigation reported improved BMD values, particularly for the legs and hips, and decreased bone turnover markers in runners compared with controls [94]. However, a separate study in male runners reflects the importance of energy balance in preserving bone mass [95]. Eight male runners completed laboratory draws before and after 3 consecutive days of 60-minute intensive treadmill running under two experimental conditions of energy balance and with a 50 % reduction in energy intake compared with estimated needs. The energy restriction trial resulted in a 15 % reduction in N-terminal pro-peptide type 1 collagen and a 17 % decrement in IGF-1, while no changes were noted for the energy balance condition [95]. The differences between the two investigations in male runners illustrate the influence on metabolism and bone health of energy intake and not participation in an endurance sport. Similarly, Dolan and colleagues [11, 85] hypothesized that observed lower BMD values in male jockeys may be the result of the demands to maintain low body weight for their sport, leading athletes to adopt restrictive eating patterns.

The most extreme example of the effect of under-nutrition on BMD during growth can be demonstrated in boys with anorexia nervosa. While much is known about the deleterious effects of poor nutrition on bone accrual and BMD in adolescent girls and young women with anorexia nervosa, much less is known about these effects in boys. Misra et al. [96] found that, compared with controls, adolescent boys with anorexia nervosa had lower BMD in the spine, hip, femoral neck, and intertrochanteric and trochanter regions, as well as throughout the whole body. A decrease in bone formation and bone resorption markers, indicating decreased bone turnover, was seen in those boys with anorexia nervosa. Testosterone and lean mass were positively associated with BMD, while IGF-1 was an important predictor for markers of bone turnover [96]. While most male athletes do not have EDs, much can be learned through the pathophysiology of anorexia nervosa in both sexes. Most concerning in this population is the low BMD and decreased bone turnover observed at a time when bone accrual is critical for attainment of peak bone mass, and the potential implications for future osteoporosis and fracture.

The relative importance of bone loading encountered in sports compared with hormonal influences and dietary factors remains unknown in terms of its contribution to bone health. For example, testosterone was not found to be suppressed or associated with lower BMD in runners [97]. Authors attributed these findings to habituation as runners were in the maintenance phase of training. Testosterone was not measured longitudinally, so an alternative explanation is that changes in testosterone may have been detected if they had been measured at multiple time points. Elite male lightweight rowers may have relatively lower testosterone concentrations with preserved bone density; however, greater testosterone concentrations and duration of participation were each associated with higher BMD. The authors attributed these findings to the relative importance of mechanical loading over suppressed hormonal concentrations [61]. Resistance training and weight training may result in a more robust anabolic response than endurance training or aerobic exercise, suggesting the mode of exercise may influence hormonal changes [98, 99].

In summary, most findings of lower sex hormones in male athletes are primarily observed in endurance athletes, and values outside the normal range appear clearly associated with impaired bone health. Mechanical forces from sports participation may modulate the effects of lower testosterone on bone health. Large variations in the range of normal values for sex hormones and other markers of bone health may mask relative deficiencies of sex hormones in these athletes, emphasizing the importance of collecting hormone concentrations longitudinally to detect changes associated with sports participation. Future studies should include suitable active control subjects to advance our understanding of the optimal physiological response to exercise that would be expected and an accurate athletic normal range for these laboratory values.

6 Conclusion and Recommendations for Future Research

Participation in sport offers many health benefits to both male and female athletes. In female athletes, the more well described and researched Triad components have the potential for negative consequences on reproductive and skeletal health, leading to low BMD, stress fractures, and other health consequences. More recent research has demonstrated that male athletes, especially those participating in sports emphasizing leanness, may experience similar adverse health consequences from physical activity and sport participation. Although research is lacking on the severity of the clinical sequelae of energy deficiency in the male athlete, the health issues appear to parallel the Triad in the female athlete, including low energy availability with or without DE, reduced sex steroids including testosterone, and impaired bone health. The influence of inadequate nutrition on impaired health in both sexes has been recently highlighted by a proposed new term by the International Olympic Committee "Relative Energy Deficiency in Sport (RED-S)" [100]. However, limitations exist in the use of this term, particularly when applying it universally to both sexes [101]. It is our recommendation to keep the well-researched and acknowledged term, the 'Female Athlete Triad', while continuing efforts to improve our knowledge of the mechanisms and outcomes that occur in active and athletic men that appear to parallel the Triad, and to better quantify these relationships. With further knowledge of the mechanisms that may be unique to each sex, evidence-based guidelines that result in best practice can be developed. This review is intended to discuss sex-specific health concerns associated with sports and exercise in both male and female athletes and to encourage additional research in these populations.

Our current understanding of the influence of nutrition on neuroendocrine function and bone health in males is limited compared with that for female athletes with the Triad. The prevalence of low energy availability may be less common than in female athletes [9]. Similarly, the health issues resulting from this condition may not be as severe or as apparent in male athletes as in female athletes. Our understanding of the consequences in women with the Triad is well-known and includes vascular disease, premature osteoporosis, and eating disorders that may result in early death [3]. Screening and return-to-play guidelines for the Triad have been developed [3]. Screening for hypogonadism during pre-participation examinations was proposed for male athletes [102], although no current evidence-based guidelines incorporate screening and risk stratification for the male athlete to reduce the risk of bone stress injuries or low BMD, and for return to play.

In male athletes who present with recurrent bone stress injuries or initial injury in trabecular regions (including pelvis, sacrum, or femoral neck), we recommend clinicians screen for and consider the evaluation of both nutrition and hormone function, especially if additional risk factors are found, such as low BMI (particularly BMI $\leq$17.5 kg/m^2 in adolescent males) [86]. Our current practice includes screening for low BMD with dual energy X-ray absorptiometry and completing a nutrition and endocrine workup, including 25-hydroxy vitamin D concentrations, as well as free and total testosterone in athletes who sustain bone stress injuries in high-risk regions, including the pelvis and femoral neck, although evidence-based guidelines are needed for further recommendations. For athletes who participate in sports emphasizing leanness or who exhibit weight-control behaviors and, thus, increased risk for low energy availability, referral to a registered dietitian with a background in sports nutrition is recommended to counsel athletes on their caloric and macronutrient intake needs specific for their sport and exercise energy expenditure. In most instances of the Triad, the treatment of underlying low energy availability and amenorrhea or prolonged oligomenorrhea by increasing energy intake and/or reducing energy expenditure is recommended over the use of oral contraceptive pills and other hormonal therapy. We emphasize that whether the evidence-based treatment and return-to-play guidelines for female athletes with the Triad are applicable for male athletes presenting a similar constellation of findings is currently unknown. Caution should be taken when applying data in women to make recommendations in men. However, until further research is available to evaluate outcomes, a non-pharmacologic approach is recommended as the first step to improving bone health in the male athlete with low energy availability and Triad-related findings, including adequate caloric, calcium, and vitamin D intake. For the general population of male and female adolescents and young adults, the Institute of Medicine recommends vitamin D 600 IU daily for bone health [103]. Calcium 1000 mg daily is recommended for men and women aged 19–50 years for bone health, while calcium 1300 mg per day is recommended to account for growth in adolescents and young adults aged 9–18 years [103].

Determining methods to encourage healthy behavior in male athletes is a challenge. World-class ski jumping has seen a decrease in BMI of 4 units since 1970, and the International Ski Federation has placed restrictions on length of ski based on weight to address unhealthy behaviors and EDs associated with weight loss in these athletes [104]. The National Collegiate Athletic Association (NCAA) modified rules to address unhealthy weight control in male wrestlers, resulting in a reduction in these behaviors [31]. Leadership from sports-governing bodies will complement efforts by physicians and other educational efforts designed to protect the health of male athletes.

Future directions for research include better characterization of nutritional deficits in male athletes, including defining energy availability in male athletes in relationship to changes in metabolic and reproductive hormones, and prospective evaluation for changes of bone health over time. Further research is recommended to evaluate the relationship with vitamin D and calcium in the male athlete that may promote bone health and reduce the risk of bone stress injuries, as well as hormonal and metabolic effects on bone. The loading characteristics of sports participation may influence the bone health of athletes; identifying loading protocols for low-impact and non-impact sports may be a method to improve bone health in these athlete populations. We have identified a limited understanding of interactions between individual components of nutrition, endocrine function, and low bone density. The true prevalence of low testosterone resulting from hypogonadotropic hypogonadism in male athletes is currently unknown [8].

Emerging research demonstrates performance decrements in women with ovarian suppression from low energy availability [105]. Similar evidence has suggested reduced testosterone concentrations and dietary restriction may decrease power in wrestlers [106, 107]. Investigation of the influence of nutrition on gonadal function and performance in men would be valuable, as improving performance is a desirable goal for athletes and may be a motivating factor that can foster healthy dietary behaviors.

Compliance with Ethical Standards

Conflict of interest and study funding Adam Tenforde, Aurelia Nattiv, Michelle Barrack, and Michael Fredericson declare they have no conflicts of interest to report related to this work. The authors thank Dr. Mary Jane De Souza for her review of our manuscript. No financial support was received for the preparation of this manuscript.

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