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Bone Health in Young Athletes: a Narrative Review of the Recent Literature

Aubrey Armento[1,2] · Marc Heronemus[3] · Daniel Truong[3] · Christine Swanson[4]

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Abstract

Purpose of Review The aim of this review is to discuss the most recent published scientific evidence regarding bone health in the pediatric athlete.

Recent Findings Pediatric athletes commonly suffer from overuse injuries to the physes and apophyses, as well as bone stress injuries, for which magnetic resonance imaging grading of the severity of injuries may be useful in guiding return to sport. Adolescent athletes, particularly those who train indoors and during the winter season, are at risk for vitamin D deficiency, which has important implications for bone mineral density. However, the relationship between vitamin D status and traumatic fracture risk is still unclear. While the female athlete triad is a well-established condition, the current work has led to the recognition of parallel pathophysiology in male athletes, referred to as the male athlete triad. Recent evidence suggests that transdermal 17β-estradiol treatment in amenorrhoeic female athletes is an effective adjunctive treatment to improve bone mineral density in treatment of the female athlete triad.

Summary Young athletes are at risk for musculoskeletal injuries unique to the growing skeleton. Optimizing nutritional intake, particularly related to adequate vitamin D intake and prevention of the athlete triad, is critical to optimize bone health in the young athlete.

Keywords Pediatric · Athlete · Sport · Bone · Injury · Triad

Introduction

In 2019, 56.1% of youth aged 6–17 years of age reported participation in organized sports [1]. There are ample benefits to youth sports participation, including enhanced mental health, social relationships, and academic achievement, as well as improved physical fitness and bone health [2]. Adolescence is a particularly important period for bone accrual, with up to 90% of peak bone mass attained by age 18 [3]. There are many special considerations for bone health in the pediatric athlete. Developmental ossification centers, including skeletal physes and apophyses, are particularly vulnerable to both acute and chronic injuries, in addition to traumatic fractures and bone stress injuries in young athletes [2]. Vitamin D status, important not only for prevention of nutritional rickets, must be considered as it relates to bone mineral density, fracture risk, and risk of deficiency in the pediatric athlete [4]. Additionally, physically active adolescents can suffer from the male and female athlete triad, defined by the interplay of low energy availability, hypogonadotropic hypogonadism

✉ Aubrey Armento
aubrey.armento@childrenscolorado.org

Marc Heronemus
marc.2.heronemus@cuanschutz.edu

Daniel Truong
daniel.truong@cuanschutz.edu

Christine Swanson
christine.swanson@cuanschutz.edu

1 Department of Orthopedics, University of Colorado School of Medicine, 13123 E. 16th Ave, B060, Aurora, CO 80045, USA

2 Sports Medicine Center, Children's Hospital Colorado, Aurora, CO, USA

3 Department of Family Medicine, University of Colorado School of Medicine, Aurora, CO, USA

4 Department of Medicine-Endocrinology, Diabetes, and Metabolism, University of Colorado School of Medicine, Aurora, CO, USA

or hypothalamic amenorrhea, and impaired bone health [5, 6]. In this narrative literature review, we summarize the most recent scientific findings regarding bone health in the young athlete, with a focus on bone injuries, vitamin D, and the athlete triad.

Methods

We conducted a literature review in the PubMed database including only English language articles published from 2019 to present, using the following terms: bone, pediatric, adolescent, athlete, sport. Pertinent studies identified from the reference lists of articles collected via PubMed were also considered. We selected, reviewed, and summarized the most recent literature into three major themes related to bone health in young athletes: (1) bone injuries, (2) vitamin D, and (3) the athlete triad.

Discussion

Bone Injuries in Young Athletes

A summary of key relevant studies on this topic area can be found in Table 1.

Physeal Injuries

Overuse injuries to the physis are unique to the pediatric athlete. Carsen et al. performed a recent narrative review of physeal development, the effects of force on the developing physis, and clinical pathologies based on anatomical location [7]. The physeal direction and rate of growth are modified based on the stress and forces acting upon it [8]. If forces exceed the capacity of the growing physis from overtraining, especially in the peripubertal years, this may lead to metaphyseal vascular supply disruption, epiphysiolysis, or injuries to the physeal plate [9-11]. Forces applied through the physes manifest as overuse injuries in different locations based on the type of sport such as in the elbow ("Little League elbow") and shoulder ("Little League shoulder") in throwing athletes and the wrist in gymnasts ("gymnast wrist") [7]. Premature physeal closure at the distal radius, growth deformity, and ulnar overgrowth can occur as a consequence of gymnast wrist in peripubertal athletes [7]. Awareness of the vulnerability of the physes to repetitive stress in young athletes is important when considering diagnoses of overuse injuries and injury prevention in this population.

Apophysitis

Apophyses—secondary bone growth centers at tendon attachment sites—can also be subject to both acute and chronic injury in pediatric athletes. Inflammation of the apophysis, or apophysitis, is a result of multiple factors including chronic stress, rapid growth, and genetics and typically presents as insidious onset of pain at the apophysis in active youth [12]. While apophysitis is an overuse injury, avulsion fractures of the apophysis occur from an acute traction injury resulting in fracture and potential apophyseal displacement [13]. A retrospective cohort study of athletes aged 5 to 18 years presenting to a sports medicine clinic with musculoskeletal complaints found 11.8% with tibial tubercle apophysitis, 10.7% with calcaneal apophysitis, and 5.5% with iliac crest apophysitis, which, including patellofemoral pain syndrome (20.4%) and rotator cuff tendinitis (5.6%), comprised the top five overuse injury diagnoses in the study [14]. Males had more apophyseal injuries than females, with baseball being the most common sport associated with overuse injuries in males, consistent with prior literature [15, 16]. Younger age groups had more apophyseal injuries, also consistent with prior literature [17-20]. Interestingly, greater than 80% of all athletes continued to play prior to clinical evaluation despite pain, indicating the need for education of youth athletes, parents, and coaches on the risks of overuse injuries. Gudelis et al. found that anterior inferior iliac spine apophyseal injuries were the most common in a study of one youth soccer club over 7 seasons, with an incident rate of 0.35 apophyseal injuries per 1000 h of training exposure [12]. Unique to this study was the use of ultrasound as the most common imaging modality to aid in diagnosis compared to plain radiographs, which are more frequently utilized in the assessment of apophyseal injuries [21, 22]. The study authors proposed ultrasound as a more useful diagnostic tool because apophyseal injuries may be missed on plain radiographs if the apophysis is not ossified depending on pubertal progression. Finally, they found significantly longer duration of recovery in apophyseal avulsion fractures compared to apophysitis in both return to training and to competition, which has not been previously reported.

Several studies examined tibial tubercle apophysitis, or inflammation at the insertion of the patellar tendon at the tibial tubercle apophysis (also known as Osgood-Schlatter's disease) [23-25]. A review of the presentation, evaluation, and treatment of tibial tubercle apophysitis highlighted that 8–13-year-old girls and 10–15-year-old boys are most at risk, with modifiable risk factors including training programs, hamstring, quadricep and calf muscle tightness, and larger body weight (kg) [21, 23, 2725-]. Tibial tubercle apophysitis is self-limited, and prevention programs should focus on regular stretching and balance training, especially for athletes who frequently perform jumping, squatting, and

Table 1 Summary of recent key studies on bone injuries in young athletes

Author, year	Type of study	Participants	Results
Gudelis et al., 2022 [12]	Prospective observational	173 male youth soccer players aged 7–19 years	Rate of apophyseal injuries was 0.35 per 1000 h of training exposure, with the anterior inferior iliac spine as the most common location (43.3%)
Valasek et al., 2019 [14]	Retrospective chart review	Patients presenting to a sports medicine clinic aged 5–18 years (43.1% male, 56.9% female)	A total of 6593 overuse injuries were included; the most frequent overuse diagnoses were patellofemoral pain syndrome (20.4%), tibia tubercle apophysitis (11.8%), calcaneal apophysitis (10.7%), rotator cuff tendinitis (5.6%), and iliac crest apophysitis (5.5%)
Kraus et al., 2019 [73]	Retrospective chart review + prospective cohort	156 male collegiate runners	Each 1-point increase in baseline cumulative athlete triad risk score was associated with a 37% increase in prospective bone stress injury risk ($p = 0.0079$)
Hoenig et al., 2022 [32]	Systematic review and meta-analysis	16 studies with 560 bone stress injuries of varying degrees of severity as determined by MRI grading	Higher MRI-based grading of bone stress injuries correlated with a longer time to return to sport ($r = 0.554$, $p = 0.001$). For grade 1, 2, 3, and 4 injuries respectively at all anatomic locations, the average time to return to sport was 41.7 days, 70.1 days, 84.3 days, and 98.5 days
Tooomey et al., 2022 [37]	Systematic review and meta-analysis	17 prospective observational studies including measures of adiposity and sports-related injury in youth under the age of 20 years	Pooled OR of the association between body mass index (BMI) and injury risk was 1.18 (95% CI: 1.03–1.34, $p = 0.01$), excluding bone stress injuries. BMI was lower in youth with bone stress injuries compared to controls

MRI, magnetic resonance imaging; *OR*, odds ratio; *BMI*, body mass index kicking. Interestingly, a different study also found reduced hip internal rotation, in addition to tighter quadriceps and limited ankle dorsiflexion in athletes with tibial tubercle apophysitis, which is the first to report reduced hip internal rotation as a risk factor [25]. This may be specific to baseball players rather than other athletes who more commonly develop tibial tubercle apophysitis, as limited internal rotation may affect the lower extremity during the throwing motion and not during jumping, squatting, or kicking [25].

One recent study examined return to play duration in professional youth soccer players with calcaneal apophysitis, or inflammation at the insertion of the Achilles tendon at the calcaneal apophysis (also known as Sever's disease), and found an average return to play duration of 60.7 days. There were no differences in return to play duration based on age or body mass index (BMI), but there was significantly longer return to play duration in athletes with bilateral or recurrent disease [28]. As calcaneal apophysitis is a common overuse injury in youth athletes, quantifying time loss due to the injury is useful information for practitioners to provide to their patients. BMI not being correlated with duration of return to play is interesting, as higher BMI is a risk factor for calcaneal apophysitis itself [29, 30].

Bone Stress Injuries (Formerly Known as "Stress Fractures")

Bone stress injuries (BSI) occur when excessive repetitive stress is applied to normal bone resulting in structural bone weakness and pain [31]. A recent editorial was published calling for the use of the term "bone stress injury," rather than "stress fracture," to describe these injuries, as the majority of BSIs do not have a discernible fracture line [31]. Return to sport after BSI varies based on the severity and location of the injuries [31]. The gold standard for diagnosis of BSIs is magnetic resonance imaging (MRI) to evaluate for the presence of periosteal edema, bone marrow edema, and fracture lines. These findings inform various MRI-based grading systems that have been developed to classify the severity of BSIs with the intent to guide the anticipated time to healing and return to sport [32]. Several studies have evaluated the correlation between MRI grading of BSIs and duration of return to sport, with mixed findings. A recent study examined 38 pediatric athletes (55% were track and/or cross-country athletes) with tibial BSIs who were compliant with treatment and found that MRI grade per the Fredericson classification [33] did not correlate with time to recovery or return to full participation in sports [34]. This is in line with prior studies that found that MRI severity grade was not significantly associated with time to recovery in adolescent and adult athletes with BSIs at different locations [35, 36]. However, a more recent systematic review and meta-analysis of 16 studies including 560 BSIs did find that higher MRI-based grading was significantly associated with increased time to return to sport [32]. Additionally, BSIs at trabecular-rich sites took longer to heal than BSIs at cortical-rich sites. Generally, MRI grading and fracture location may be useful for prognostication of return to sport after BSI, while also considering clinical presentation and other associated risk factors [32].

Considering other risk factors for BSI, a 2022 systematic review and meta-analysis of 17 prospective observational studies examined the relationship between adiposity and sports injury risk in young athletes, including BSIs [37]. Young athletes with a BSI were more likely to have a lower BMI than uninjured peers. This was in contrast to all sport-related injuries and lower extremity injuries for which higher BMI, not lower, was a risk factor. Low BMI should prompt clinicians to screen for other risk factors for BSIs, such as the athlete triad noted in more detail below.

Traumatic Fractures

The most common location for traumatic fractures in youth is the lower forearm (distal radius), but fracture location varies based on sport/activity type [38, 39]. In a recent epidemiological study of distal radius fractures in children 4–18 years old, 33.5% occurred due to a high-energy fall, and 28.4% were related to sports participation, with soccer (27.3%), football (20.9%), and basketball (15.7%) as the most common sports [40]. Participation in high-impact sports (such as gymnastics, karate, and volleyball) during adolescence has many skeletal benefits, including increased bone mass and decreased rates of osteoporosis later in life [41, 42]. However, it was hypothesized that participation in these sports may also increase athletes' risk for traumatic fractures. A recent 12-month longitudinal study of 285 adolescents examined the association between sports participation and fracture risk [43]. Sports participation was not significantly correlated with incidence of traumatic fractures compared to peers not engaged in sports regardless of sport type (martial arts, impact sports, or swimming) [43]. This was consistent with prior findings [44-46], suggesting that the long-term benefits of youth sports participation likely outweigh the risk of acute fractures related to sport.

Vitamin D and Bone Health

The importance of vitamin D for bone health is well-established, and young athletes can be at risk for vitamin D insufficiency and deficiency, particularly in those who train mostly indoors, during the winter months, and in those who wear protective equipment that limits skin exposure to the sun [4, 47]. Although the definitions of vitamin D deficiency and insufficiency are often debated, a group of pediatric endocrinology societies released a global consensus statement in 2016 defining serum 25-hydroxyvitamin

D (25(OH)D) level < 12 ng/mL (< 30 nmol/L) as deficient, 12–20 ng/mL (30–50 nmol/L) as insufficient, and > 20 ng/mL (> 50 nmol/L) as sufficient [48]. Using these cut-offs, a recent study by Herrick et al. reviewed vitamin D status from the National Health and Nutrition Examination Survey (NHANES) 2011–2014 and showed that the prevalence of vitamin D insufficiency and deficiency in adolescents between the ages of 12–19 was 22.7% and 4.8% respectively [49]. Low dietary calcium intake, physical inactivity, obesity, dark skin pigment, northern geographic location, low exposure to sunlight, and history of fractures are associated with low vitamin D, which has important implications for attainment of optimal peak bone mineral density (BMD) in adolescence [50-53]. A study by Song et al. analyzed the association between vitamin D status and BMD with data from the Korea National Health and Nutritional Examination Survey. In a group of 1063 adolescents, they found that higher vitamin D levels were correlated with higher BMD *Z*-scores at the lumbar spine and femoral neck, after adjusting for calcium intake, physical activity, and BMI [53]. A summary of key relevant studies on this topic area can be found in Table 2.

Vitamin D and Physical Activity

Several recent studies evaluated the relationships between vitamin D status, physical activity, and bone health. Mesquita et al. assessed 25(OH)D levels, BMD, and bone geometry of 32 adolescent athletes in weight-bearing sports (artistic gymnastics and track & field) compared to 43 non-sport adolescents. They found that those participants with 25(OH)D levels (defined as ≥ 27 ng/mL based on the median values of the sample) in combination with sports participation had higher areal BMD of the whole body, greater trochanter, femoral neck, femoral shaft, and whole femur, as well as greater cross-sectional area of the femoral neck, than those with low 25(OH)D levels (< 27 ng/mL) and no sports participation [51]. Constable et al. evaluated the independent and interactive associations of vitamin D status, physical activity, and BMD in 366 prepubertal Finnish children aged 6–8 years. They discovered that while the amount of moderate and moderate-to-vigorous physical activity and 25(OH)D levels were both independently associated with total body less head and lower limb BMD, there were not interactions between physical activity intensity and 25(OH)D levels with BMD, suggesting that these may be independent determinants of BMD in prepubertal children [54].

Vitamin D levels can vary throughout the year, which can be affected by the season of the sport, sun exposure, and home isolation (such as the COVID-19 lockdown). A study conducted by Jastrzębska et al. in Poland evaluated 35 adolescent soccer players throughout the autumn season and found that 77% of players had optimal 25(OH)D levels (> 30 ng/mL) at the beginning of the season but only 14% of players maintained optimal levels by the end of the season [55]. A follow-up study published in 2022 assessed 25(OH)D levels of 24 elite young soccer players throughout an entire calendar year and found that the highest levels were during August and September months when there was more sunlight exposure in Northern Europe. In contrast, the lowest 25(OH)D levels were found in the months of May and December after more indoor training occurred [56]. During this study, there was the unexpected COVID-19 lockdown, which lead to lower vitamin D levels, likely secondary to less sunlight exposure. Interestingly, the group that received vitamin D supplementation (5000 IU daily) from January to March did not demonstrate significantly higher 25(OH)D levels at follow-up compared to the no supplementation group [56].

Vitamin D and Fractures

Fractures in children are common, accounting for 10–25% of accidents and injuries in the pediatric population [50, 57]. Bone fractures have a negative impact on daily activities and participation in sports, and also can be financially and socially impactful for families due to the increased amount of care and attention bone fractures require [50]. Vitamin D deficiency can lead to nutritional rickets in children, leading to reduced bone mineralization and increased fracture risk [48]. While it is accepted that vitamin D is important for bone mineralization, the role of vitamin D in bone fracture prevention in children and adolescents is still debated [50, 57]. Therefore, understanding whether 25(OH)D levels have a meaningful impact on fracture risk is crucial. Yang et al. recently published a systematic review and meta-analysis study on the relationship between 25(OH)D levels and fracture in children and adolescents. In the 7929 subjects from 23 studies, lower 25(OH)D levels were associated with increased risk of fractures, particularly those with 25(OH)D < 20 ng/mL [57]. In contrast, a recent systematic review and meta-analysis study by Zheng et al., which included 3943 subjects from 13 studies, concluded that there was no significant relationship between 25(OH)D levels and risk of fracture in children [50]. The conclusions of these studies highlight that there is no consensus on whether low 25(OH)D levels are significantly related to increased risk of bone fractures in the pediatric population. The discrepant findings may be related to the variation in studies included in both meta-analysis, as well as the statistical approach, but both highlight the need for future prospective randomized controlled trials to better understand what role, if any, vitamin D has in fracture risk reduction in children. However, it is important to note that there is no evidence that vitamin D increases the risk of fractures and ensuring adequate vitamin D status is necessary for the prevention of nutritional rickets in the pediatric population [48].

Table 2 Summary of key studies on vitamin D in young athletes

Author, year	Type of study	Participants	Results
Song et al., 2021 [50]	Cross-sectional	1063 adolescents from the Korea National Health and Nutritional Examination Survey (53.7% male, 46.3% female)	Vitamin D deficiency, insufficiency, and sufficiency comprised 20.5%, 58.6%, and 20.9% of all subjects, respectively. Bone mineral density *Z*-scores at the lumbar spine, whole body, and femoral neck were positively associated with 25(OH)D levels (all $p<0.05$) after controlling for calcium intake, physical activity, and lean and fat mass *Z*-scores
Jastrzębska et al., 2022 [53]	Prospective cohort	24 elite male youth soccer players	25(OH)D levels were highest in September and then the following August over the year-long study, and lowest in the winter months. There were no significant differences in 25(OH)D levels over the year in those who were and were not supplementing with vitamin D during the winter months
Mesquita et al., 2022 [48]	Cross-sectional	75 adolescents (32 in the sporting group (12 boys, 20 girls), 43 in the non-sporting group (29 boys, 14 girls))	Adolescents in the sporting group with higher 25(OH)D levels (≥ 27 ng/mL) demonstrated higher areal bone mineral density of whole body ($p=0.035$), greater trochanter ($p=0.001$), femoral shaft ($p=0.019$), femoral neck ($p=0.005$), and whole femur ($p=0.003$) compared to the non-sport/low vitamin D (< 27 ng/mL) group
Zheng et al., 2021 [47]	Systematic review and meta-analysis	13 studies with 3943 participants 18 years old or younger (1373 subjects in the fracture group, 2570 in control group) assessing 25(OH)D levels/vitamin D status and fracture occurrence	There were no significant differences in the proportion of subjects with vitamin D deficiency (< 20 ng/mL) between fracture and control groups (OR = 1.22, 95% CI: 0.96 to 1.56, $p=0.64$)
Yang et al., 2021 [54]	Systematic review and meta-analysis	17 case–control and 6 cross-sectional (2929 fracture cases and 5000 controls) of participants 18 years old or younger assessing 25(OH)D levels/vitamin D status and fracture occurrence	25(OH)D levels were lower in fracture cases than in controls (pooled MD = − 3.5 nmol/L, 95% CI: − 5.60 to − 1.42). Pooled OR of fracture risk in subjects with vitamin D deficiency (< 20 ng/mL) = 1.29 (95% CI: 1.10 to 1.53) compared to those with levels > 20 ng/mL

25(OH)D, 25-hydroxyvitamin D; *OR*, odds ratio; *CI*, confidence interval; *MD*, mean difference

The Male and Female Athlete Triad

Updates on the Female Athlete Triad

The first position stand on the female athlete triad was published by the American College of Sports Medicine in 1997 [58]. It outlined the three interrelated components of the triad to include disordered eating, amenorrhea, and osteoporosis [58]. Since that time, several more iterations on the female athlete triad have been published up to the most recent consensus statement in 2014 [5]. The components of the triad have evolved to be defined as (1) low energy availability with or without disordered eating, (2) menstrual dysfunction, and (3) low BMD [5]. The most clinically significant outcomes of the triad include clinical eating disorders, amenorrhea, and osteoporosis; however, many athletes suffer from less severe but still harmful conditions such as reduced energy availability without disordered eating, subclinical menstrual disturbances (i.e., anovulation and luteal phase defects), and low BMD without osteoporosis [5]. A review of the recent literature by Logue et al. regarding low energy availability in athletes reported 22–58% of adolescent and young adult female athletes with low energy availability, up to 47.9% with menstrual dysfunction, and up to 22.7% with low BMD [59].

The primary etiology of the triad is low energy availability, or lack of adequate energy to support physiologic functioning after removing the energy expenditure from exercise, leading to various hormonal alterations [60]. Energy availability is calculated as follows: $\frac{[\text{Energy intake (kcal)} - \text{Exercise energy expenditure (kcal)}]}{\text{Fat-free mass (kg)}}$ [61]. From rigorously controlled trials of adult women, the threshold of low energy availability, or the level at which metabolic and hormonal alterations occur, has been deemed < 30 kcal/kg of fat-free mass. However, energy availability thresholds are subject to individual variability and have not been clearly delineated in the pediatric population [61]. The hormonal disturbances that occur in the setting of low energy availability, particularly hypoestrogenism, lead to not only declines in areal BMD (aBMD), but also impairments in bone microarchitecture and strength [60]. In the period of adolescence during peak bone mass accrual, low energy availability and its downstream effects on bone may result in lack of attainment of optimal bone mass [62]. In a recent study by Singhal et al., comparisons of aBMD and bone strength estimates between oligo-amenorrhoeic and eumenorrheic young athletes and non-athletes demonstrated significantly higher aBMD and aBMD *Z*-scores at the total hip in eumenorrheic athletes compared to oligo-amenorrhoeic athletes and non-athletes at baseline and at 12-month follow-up [62]. Eumenorrheic athletes had higher failure loads, suggesting greater estimated bone strength, at the weight-bearing tibia compared to non-athletes (at baseline and 12 months) and oligo-amenorrhoeic athletes (at 12 months), although this became non-statistically significant after adjusting for changes in weight in addition to other covariates. Across the 12-month period, there were no significant differences in change in aBMD between the three groups. The key takeaways of this study are that despite the weight-bearing exercise of oligo-amenorrhoeic athletes, their aBMD and bone strength estimates did not significantly differ from non-athletes, suggesting that hypoestrogenism negates the benefit of weight-bearing exercise on bone and may account for the increased risk of lower extremity BSIs. Additionally, oligo-amenorrhoeic athletes did not demonstrate “catch-up” of aBMD over the 12-month period despite nutrition intervention and 40% of the group resuming spontaneous menstruation [62]. This is in line with prior studies revealing both reduced aBMD [63] and impaired bone microarchitecture [64] in amenorrhoeic adolescent athletes compared to eumenorrheic athletes and controls, as well as the long-term negative effect of amenorrhea on bone health and ability to achieve peak bone mass in young athletes [65]. Further research is needed to better understand the combined and independent effects of both amenorrhea and low energy availability on bone density, microarchitecture, and strength.

Specifics on the evaluation and diagnosis of the female athlete triad are beyond the scope of this review, but readers can reference the 2014 Female Athlete Triad Coalition consensus statement [5] as well as the Endocrine Society’s 2017 practice guidelines on functional hypothalamic amenorrhea [66] for more information.

There have been several important studies published in the last few years regarding treatment of the female athlete triad. The first line of treatment continues to be non-pharmacologic management to address the underlying energy deficiency and restore adequate energy status. This is typically achieved in a multidisciplinary manner with a team including but not limited to a clinician experienced in treating the triad, a sports dietitian, and a mental health practitioner if there is any concern for disordered eating, body dysmorphia, or other psychological issues contributing to the low energy availability [5]. Assessment of energy availability can be performed with a sports dietitian who will calculate dietary energy intake and exercise energy expenditure to identify energy deficiency and create an individualized nutrition plan to meet the athlete’s needs. Energy needs vary widely in young athletes based on age, sex, growth, pubertal status, and sport/exercise type. The following include the recommended dietary intake of macronutrients for adolescent athletes: protein: 0.8–1.0 g/kg/day; carbohydrates: 3–5 g/kg/day (for low intensity activity) up to 8–12 g/kg/day (for high intensity training); and fat as 20–35% of total energy intake [67]. The dietitian can also assess for micronutrient deficiencies, mostly commonly iron, vitamin D, and calcium, and make recommendations for supplementation if medically warranted, preferably guided by laboratory testing [67].

In the event that an athlete may be unsuccessful with lifestyle changes to address energy availability, has a decline in BMD, or has a new fracture over the course of 1 year of non-pharmacologic management, then the pharmacological treatment should be considered [5]. Combined oral contraceptives (COCs) are often prescribed to treat functional hypothalamic amenorrhea, despite there being limited data to support this practice [68]. A recent randomized clinical trial led by Ackerman et al. compared changes in BMD [69] and bone geometry and microarchitecture [70] in 14–25-year-old oligo-amenorrhoeic, normal weight, female athletes treated with transdermal 17β-estradiol versus a common COC versus no estrogen. Participants were randomized into (1) a PATCH group ($n=43$) that received 100 mcg of transdermal 17β-estradiol applied twice weekly and 200 mg of cyclic micronized progesterone for 12 days each month, (2) a PILL group ($n=40$) that received COC containing 30 µg ethinyl estradiol with 0.15 mg desogestrel, or (3) NONE ($n=38$) who received no estrogen or progesterone. After 12 months of treatment with 73 participants completing the entire study (PATCH: $n=25$; PILL: $n=22$; NONE: $n=26$), the researchers found that BMD and BMD *Z*-scores at the lumbar spine and femoral neck were significantly greater in the PATCH vs PILL and NONE groups, and significantly greater in the PATCH vs PILL group (but not NONE) at the total hip [69]. In the same study population, high-resolution peripheral computed tomography (HR-pQCT) was performed at baseline and 12 months, with findings demonstrating significantly greater percent increases in total and trabecular volumetric BMD, cortical area, cortical thickness, and trabecular number in the PATCH vs PILL group at the weight-bearing distal tibia [70].

These studies were the first to compare the effects of transdermal 17β-estradiol versus COC on bone outcomes in young female athletes with oligo-amenorrhea, and the first to demonstrate the greater efficacy of transdermal 17β-estradiol in improving BMD, bone geometry, and microarchitecture compared to COCs. One proposed explanation for these findings is that 17β-estradiol, the physiological form of estradiol, does not undergo first-pass metabolism in the liver, therefore bypassing the downregulation of insulin-like growth factor-1 (IGF-1) as occurs with ethinyl estradiol in COCs [69]. With assessment of bone markers in the same study population, Singhal et al. reported a significant decline in IGF-1 in the PILL group compared to the PATCH and NONE groups, which supports this explanation [71]. Additionally, ethinyl estradiol (in COCs) stimulates sex hormone-binding globulin, which may lower bioavailable estradiol, leading to negative impacts on bone accrual [69, 70]. The conclusion of these studies was that transdermal 17β-estradiol (with cyclic progesterone) should be considered an adjunct treatment for young female athletes with oligo-amenorrhea to improve skeletal health, while also focusing on non-pharmacologic measures to restore energy availability. However, future research is necessary to understand how different estradiol formulations and doses in COCs may impact bone health, the role of progesterone supplementation, and how these findings translate to fracture and bone stress injury risk.

The Male Athlete Triad

Research over the last decade has led to the recognition of the athlete triad in male athletes [72], culminating in a two-part consensus statement on the male athlete triad published in 2021 [6, 73]. Like the female athlete triad, the male athlete triad includes low energy availability with and without disordered eating and low BMD, but with hypogonadotropic hypogonadism in place of menstrual dysfunction [6]. Male athletes can experience suppressed testosterone and luteinizing hormone concentrations and pulse frequency leading to impaired spermatogenesis and decreased libido in the setting of energy deficiency and/or high-volume exercise training [6]. It appears that low energy availability and hypogonadism impair bone health with declines in BMD in male athletes, particularly in sports that emphasize leanness [6]. The prevalence of low energy availability in adolescent male athletes is understudied but has been reported to be as high as 24–56% [74, 75]. Low BMD *Z*-scores (<-1.0) at the lumbar spine have been reported in 21–23.5% of male adolescent runners, significantly associated with low body mass index (BMI) and the belief that "thinner is faster" [76], as well as low body weight and higher cumulative weekly running mileage >30 miles in the past year [77].

The Male Athlete Triad Coalition consensus statement recommends screening young male athletes for the triad starting in middle or high school and through college for early identification of those at risk to optimize bone health during the critical years of adolescence [73]. This should be done at the time of the preparticipation physical examination, and when an athlete presents with any one component of the triad [73]. These recommendations mirror those outlined for young female athletes, and the suggested screening questions for both male and female athletes can be found in Fig. 1 [5, 73]. Using baseline responses from the triad screening questions, in addition to individual BMI, BMD *Z*-scores, and number of prior BSIs, to calculate a cumulative risk score, Kraus et al. found that each 1-point increase in the cumulative risk score was associated with a 37% increase in prospective BSI risk in a group of collegiate male runners, consistent with findings in female athletes [78].

Evaluation of the male athlete triad involves the following suggested laboratory studies: complete blood count, comprehensive metabolic panel, thyroid-stimulating hormone, free T4, total +/− free T3, and 25-OH vitamin D, as well

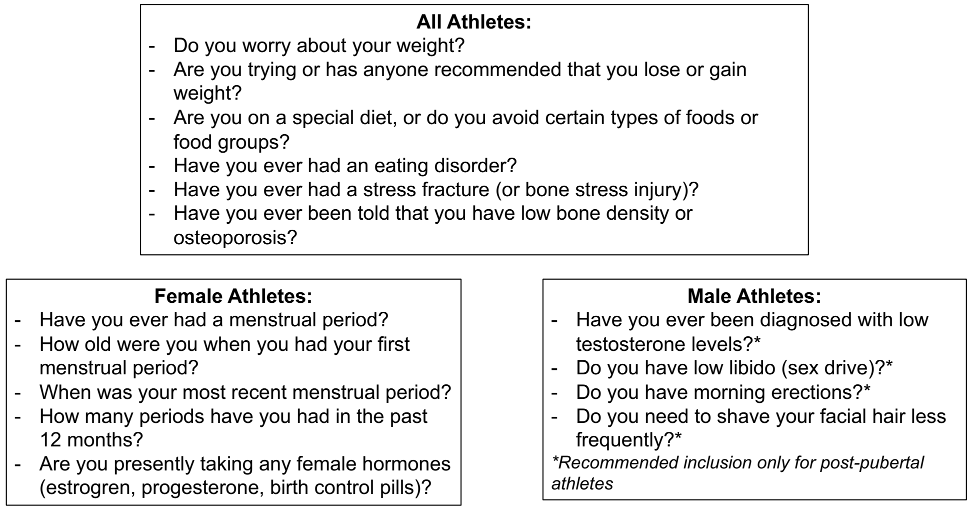

Fig. 1 Recommended screening questions for the Female and Male Athlete Triad, adapted from the Female and Male Athlete Triad Coalition consensus statements [5, 73]

as total and free testosterone [73]. The Male Athlete Triad Coalition consensus statement suggests a total testosterone cut-off of less than 8 nmol/L as clinical testosterone deficiency [6], with further laboratory assessment for those with testosterone deficiency or in the “gray zone” (8–12 nmol/L total testosterone) to include luteinizing hormone, follicle-stimulating hormone, prolactin, iron studies, erythrocyte sedimentation rate, and C-reactive protein [73]. Assessment of energy availability, disordered eating, and bone health with dual X-ray absorptiometry (DXA) is also indicated [73]. Similar to the approach for the female athlete triad, criteria for obtaining a DXA scan in male athletes are based on risk factor assessment, including BMI, % median BMI or percentage of weight loss/month, presence of a clinical eating disorder or history of disordered eating behaviors, number of prior BSIs, and prior BMD *Z*-scores if a DXA was obtained previously [73]. For pediatric patients under the age of 19, total body (less head) and lumbar spine sites should be assessed by DXA [79]. While the diagnosis of osteoporosis requires an aBMD *Z*-score ≤ -2.0 with a clinically significant fracture history, it is recommended that a *Z*-score of < -1.0 for male athletes participating in weight-bearing sports be used as the threshold for low BMD, especially in the setting of additional triad risk factors [73]. Like the management of the female athlete triad, the first line of treatment is addressing the underlying energy deficiency and restoring adequate energy status. Data is lacking regarding the safety and efficacy of pharmacologic therapies including testosterone replacement [73].

Relative Energy Deficiency in Sport (RED-S)

The 2014 and 2018 consensus statements on RED-S [61, 80] outline the physiological, psychological, and performance impairments that occur in the setting of low energy availability [61]. The RED-S expands the female athlete triad to highlight the multiple other body systems affected by energy deficiency [61]. While the focus of this review is on bone health in the young athlete, it is important to acknowledge the other implications of low energy availability in athletes, and the need for more research to better understand these relationships and lifelong consequences in the young athlete population.

Conclusion

When approaching the pediatric athlete, clinicians and researchers should consider the unique attributes of the growing skeleton and how this relates to musculoskeletal injury incidence and risk. BSIs are an inherent risk due to the repetitive nature of sport and can occur in the setting of low BMD related to the athlete triad. Adequate vitamin D status is important for BMD in the adolescent, and young athletes, especially those with less sunlight exposure, are at risk for vitamin D insufficiency/deficiency. The female athlete triad can lead to suboptimal bone accrual despite regular weight-bearing activity in female adolescent athletes. Recent evidence demonstrates that in addition to addressing the underlying low energy availability, transdermal estradiol should be considered an adjunct treatment for young female athletes with oligo-amenorrhea to improve skeletal health. It is essential to recognize that young male athletes can suffer from the male athlete triad, a condition that parallels the female athlete triad and can lead to reduced BMD in the setting of low energy availability and reproductive hormonal suppression.

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Compliance with Ethical Standards

Conflict of Interest All authors have no conflicts of interest to disclose.

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References

1. Youth sports facts: participation rates. The Aspen Institute project play, Aspen Institute Utah State University, Louisiana Tech University, TeamSnap youth sports parent surveys, 2021 and 2022, n.d. https://www.aspenprojectplay.org/youth-sports/facts/participation-rates. Accessed 20 Feb 2023.
2. McKay CD, Cumming SP, Blake T. Youth sport: friend or foe? Best Pract Res Clin Rheumatol. 2019;33:141–57. https://doi.org/10.1016/j.berh.2019.01.017.
3. Golden NH, Abrams SA; Committee on Nutrition. Optimizing bone health in children and adolescents. Pediatrics 2014;134:e1229–43 https://doi.org/10.1542/peds.2014-2173.
4. Owens DJ, Fraser WD, Close GL. Vitamin D and the athlete: emerging insights. Eur J Sport Sci. 2015;15:73–84. https://doi.org/10.1080/17461391.2014.944223.
5. Souza MJD, Nattiv A, Joy E, Misra M, Williams NI, Mallinson RJ, et al. 2014 Female Athlete Triad Coalition consensus statement on treatment and return to play of the female athlete triad: 1st International Conference held in San Francisco, California, May 2012 and 2nd International Conference held in Indianapolis, Indiana, May 2013. Br J Sports Med. 2014;48:289–289. https://doi.org/10.1136/bjsports-2013-093218.
6. Nattiv A, De Souza MJ, Koltun KJ, Misra M, Kussman A, Williams NI, et al. The male athlete triad—a consensus statement from the Female and Male Athlete Triad Coalition part 1: definition and scientific basis. Clin J Sport Med. 2021;31:335–48. https://doi.org/10.1097/JSM.0000000000000946.
7. Carsen S, Grammatopoulos G, Zaltz I, Ward L, Smit K, Beaulé PE. The effects of physical activity on physeal and skeletal development. JBJS Rev 2021;9(10). doi: 10.2106/JBJS.RVW.21.00060. https://doi.org/10.2106/JBJS.RVW.21.00060.
8. Arkin AM, Katz JF. The effects of pressure on epiphyseal growth; the mechanism of plasticity of growing bone. J Bone Joint Surg Am 1956;38-A:1056–76.
9. Jaramillo D, Laor T, Zaleske DJ. Indirect trauma to the growth plate: results of MR imaging after epiphyseal and metaphyseal injury in rabbits. Radiology. 1993;187:171–8. https://doi.org/10.1148/radiology.187.1.8451408.
10. Laor T, Wall EJ, Vu LP. Physeal widening in the knee due to stress injury in child athletes. AJR Am J Roentgenol. 2006;186:1260–4. https://doi.org/10.2214/AJR.04.1606.
11. Jónasson PS, Ekström L, Hansson H-A, Sansone M, Karlsson J, Swärd L, et al. Cyclical loading causes injury in and around the porcine proximal femoral physeal plate: proposed cause of the development of cam deformity in young athletes. J Exp Orthop. 2015;2:6. https://doi.org/10.1186/s40634-015-0022-4.
12. Gudelis M, Perez LT, Cabello JT, Leal DM, Monaco M, Sugimoto D. Apophysitis among male youth soccer players at an elite soccer academy over 7 seasons. Orthop J Sports Med. 2022;10:23259671211065064. https://doi.org/10.1177/23259671211065063.
13. Davis KW. Imaging pediatric sports injuries: lower extremity. Radiol Clin North Am. 2010;48:1213–35. https://doi.org/10.1016/j.rcl.2010.07.004.
14. Valasek AE, Young JA, Huang L, Singichetti B, Yang J. Age and sex differences in overuse injuries presenting to pediatric sports medicine clinics. Clin Pediatr (Phila). 2019;58:770–7. https://doi.org/10.1177/0009922819837360.
15. Moyer JE, Brey JM. Shoulder injuries in pediatric athletes. Orthop Clin North Am. 2016;47:749–62. https://doi.org/10.1016/j.ocl.2016.05.003.
16. Tisano BK, Estes AR. Overuse injuries of the pediatric and adolescent throwing athlete. Med Sci Sports Exerc. 2016;48:1898–905. https://doi.org/10.1249/MSS.0000000000000998.
17 Patel DR, Yamasaki A, Brown K. Epidemiology of sports-related musculoskeletal injuries in young athletes in United States. Transl Pediatr. 2017;6:160–6. https://doi.org/10.21037/tp.2017.04.08.
18. Soligard T, Schwellnus M, Alonso J-M, Bahr R, Clarsen B, Dijkstra HP, et al. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. Br J Sports Med. 2016;50:1030–41. https://doi.org/10.1136/bjsports-2016-096581.
19. Arnold A, Thigpen CA, Beattie PF, Kissenberth MJ, Shanley E. Overuse physeal injuries in youth athletes. Sports Health. 2017;9:139–47. https://doi.org/10.1177/1941738117690847.
20. Leppänen M, Pasanen K, Kannus P, Vasankari T, Kujala UM, Heinonen A, et al. Epidemiology of overuse injuries in youth team sports: a 3-year prospective study. Int J Sports Med. 2017;38:847–56. https://doi.org/10.1055/s-0043-114864.
21. Gholve PA, Scher DM, Khakharia S, Widmann RF, Green DW. Osgood Schlatter syndrome. Curr Opin Pediatr. 2007;19:44–50. https://doi.org/10.1097/MOP.0b013e328013dbea.
22. Ramponi DR, Baker C. Sever's disease (calcaneal apophysitis). Adv Emerg Nurs J. 2019;41:10–4. https://doi.org/10.1097/TME.0000000000000219.
23. Ladenhauf HN, Seitlinger G, Green DW. Osgood-Schlatter disease: a 2020 update of a common knee condition in children. Curr Opin Pediatr. 2020;32:107–12. https://doi.org/10.1097/MOP.0000000000000842.
24. Rathleff MS, Graven-Nielsen T, Hölmich P, Winiarski L, Krommes K, Holden S, et al. Activity modification and load management of adolescents with patellofemoral pain: a prospective intervention study including 151 adolescents. Am J Sports Med. 2019;47:1629–37. https://doi.org/10.1177/0363546519843915.
25. Omodaka T, Ohsawa T, Tajika T, Shiozawa H, Hashimoto S, Ohmae H, et al. Relationship between lower limb tightness and practice time among adolescent baseball players with symptomatic Osgood-Schlatter disease. Orthop J Sports Med. 2019;7:2325967119847978. https://doi.org/10.1177/2325967119847978.
26. de Lucena GL, dos Santos GC, Guerra RO. Prevalence and associated factors of Osgood-Schlatter syndrome in a population-based sample of Brazilian adolescents. Am J Sports Med. 2011;39:415–20. https://doi.org/10.1177/0363546510383835.
27. Nakase J, Goshima K, Numata H, Oshima T, Takata Y, Tsuchiya H. Precise risk factors for Osgood-Schlatter disease. Arch Orthop Trauma Surg. 2015;135:1277–81. https://doi.org/10.1007/s00402-015-2270-2.
28. Belikan P, Färber L-C, Abel F, Nowak TE, Drees P, Mattyasovszky SG. Incidence of calcaneal apophysitis (Sever's disease) and return-to-play in adolescent athletes of a German youth soccer academy: a retrospective study of 10 years. J Orthop Surg Res. 2022;17:83. https://doi.org/10.1186/s13018-022-02979-9.
29. James AM, Williams CM, Haines TP. Health related quality of life of children with calcaneal apophysitis: child & parent perceptions. Health Qual Life Outcomes. 2016;14:95. https://doi.org/10.1186/s12955-016-0497-4.
30. James AM, Williams CM, Luscombe M, Hunter R, Haines TP. Factors associated with pain severity in children with calcaneal apophysitis (Sever disease). J Pediatr. 2015;167:455–9. https://doi.org/10.1016/j.jpeds.2015.04.053.

31. Warden SJ, Hoenig T, Sventeckis AM, Ackerman KE, Tenforde AS. Not all bone overuse injuries are stress fractures: it is time for updated terminology. Br J Sports Med. 2023;57:76–7. https://doi.org/10.1136/bjsports-2022-106112.
32. Hoenig T, Tenforde AS, Strahl A, Rolvien T, Hollander K. Does magnetic resonance imaging grading correlate with return to sports after bone stress injuries? A systematic review and meta-analysis. Am J Sports Med. 2022;50:834–44. https://doi.org/10.1177/0363546521993807.
33 Fredericson M, Bergman AG, Hoffman KL, Dillingham MS. Tibial stress reaction in runners. Correlation of clinical symptoms and scintigraphy with a new magnetic resonance imaging grading system. Am J Sports Med. 1995;23:472–81. https://doi.org/10.1177/036354659502300418.
34. Ditmars FS, Ruess L, Young CM, Hu HH, MacDonald JP, Ravindran R, et al. MRI of tibial stress fractures: relationship between Fredericson classification and time to recovery in pediatric athletes. Pediatr Radiol. 2020;50:1735–41. https://doi.org/10.1007/s00247-020-04760-8.
35. Yao L, Johnson C, Gentili A, Lee JK, Seeger LL. Stress injuries of bone: analysis of MR imaging staging criteria. Acad Radiol. 1998;5:34–40. https://doi.org/10.1016/s1076-6332(98)80009-3.
36. Beck BR, Bergman AG, Miner M, Arendt EA, Klevansky AB, Matheson GO, et al. Tibial stress injury: relationship of radiographic, nuclear medicine bone scanning, MR imaging, and CT severity grades to clinical severity and time to healing. Radiology. 2012;263:811–8. https://doi.org/10.1148/radiol.12102426.
37. Toomey CM, Whittaker JL, Richmond SA, Owoeye OB, Patton DA, Emery CA. Adiposity as a risk factor for sport injury in youth: a systematic review. Clin J Sport Med. 2022;32:418–26. https://doi.org/10.1097/JSM.0000000000000927.
38. Naranje SM, Erali RA, Warner WC, Sawyer JR, Kelly DM. Epidemiology of pediatric fractures presenting to emergency departments in the United States. Journal of Pediatric Orthopaedics. 2016;36:e45–8. https://doi.org/10.1097/BPO.0000000000000595.
39. Randsborg P-H, Gulbrandsen P, Šaltyte Benth J, Sivertsen EA, Hammer O-L, Fuglesang HFS, et al. Fractures in children: epidemiology and activity-specific fracture rates. JBJS 2013;95:e42. https://doi.org/10.2106/JBJS.L.00369.
40. Shah AS, Guzek RH, Miller ML, Willey MC, Mahan ST, Bae DS, et al. Descriptive epidemiology of isolated distal radius fractures in children: results from a prospective multicenter registry. Journal of Pediatric Orthopaedics. 2023;43:e1-8. https://doi.org/10.1097/BPO.0000000000002288.
41. Mantovani AM, de Lima MCS, Gobbo LA, Ronque ERV, Romanzini M, Turi-Lynch BC, et al. Adults engaged in sports in early life have higher bone mass than their inactive peers. J Phys Act Health. 2018;15:516–22. https://doi.org/10.1123/jpah.2017-0366.
42. Tenforde AS, Fredericson M. Influence of sports participation on bone health in the young athlete: a review of the literature. PM R. 2011;3:861–7. https://doi.org/10.1016/j.pmrj.2011.05.019.
43. Lynch KR, Anokye NK, Vlachopoulos D, Barbieri FA, Turi-Lynch BC, Codogno JS, et al. Impact of sports participation on incidence of bone traumatic fractures and health-care costs among adolescents: ABCD - Growth Study. Phys Sportsmed. 2020;48:298–303. https://doi.org/10.1080/00913847.2019.1685859.
44. Detter F, Rosengren BE, Dencker M, Lorentzon M, Nilsson J-Å, Karlsson MK. A 6-year exercise program improves skeletal traits without affecting fracture risk: a prospective controlled study in 2621 children. J Bone Miner Res. 2014;29:1325–36. https://doi.org/10.1002/jbmr.2168.
45. Fritz J, Cöster ME, Nilsson J-Å, Rosengren BE, Dencker M, Karlsson MK. The associations of physical activity with fracture risk–a 7-year prospective controlled intervention study in 3534 children. Osteoporos Int. 2016;27:915–22. https://doi.org/10.1007/s00198-015-3311-y.
46. Lynch KR, Kemper HCG, Turi-Lynch B, Agostinete RR, Ito IH, Luiz-De-Marco R, et al. Impact sports and bone fractures among adolescents. J Sports Sci. 2017;35:2421–6. https://doi.org/10.1080/02640414.2016.1272708.
47. Sale C, Elliott-Sale KJ. Nutrition and athlete bone health. Sports Med. 2019;49:139–51. https://doi.org/10.1007/s40279-019-01161-2.
48. Munns CF, Shaw N, Kiely M, Specker BL, Thacher TD, Ozono K, et al. Global consensus recommendations on prevention and management of nutritional rickets. J Clin Endocrinol Metab. 2016;101:394–415. https://doi.org/10.1210/jc.2015-2175.
49. Herrick KA, Storandt RJ, Afful J, Pfeiffer CM, Schleicher RL, Gahche JJ, et al. Vitamin D status in the United States, 2011–2014. Am J Clin Nutr. 2019;110:150–7. https://doi.org/10.1093/ajcn/nqz037.
50. Zheng C, Li H, Rong S, Liu L, Zhen K, Li K. Vitamin D level and fractures in children and adolescents: a systematic review and meta-analysis. J Bone Miner Metab. 2021;39:851–7. https://doi.org/10.1007/s00774-021-01238-x.
51 ED de Mesquita L, Exupério IN, Agostinete RR, Luiz-de-Marco R, da Silva JCM, Maillane-Vanegas S, et al. The combined relationship of vitamin D and weight-bearing sports participation on areal bone density and geometry among adolescents: ABCD - Growth Study. Journal of Clinical Densitometry. 2022;25:674–81. https://doi.org/10.1016/j.jocd.2022.09.001.
52. Ducic S, Milanovic F, Lazovic M, Bukva B, Djuricic G, Radlovic V, et al. Vitamin D and forearm fractures in children preliminary findings: risk factors and correlation between low-energy and high-energy fractures. Children. 2022;9:762. https://doi.org/10.3390/children9050762.
53. Song K, Kwon A, Chae HW, Suh J, Choi HS, Choi Y, et al. Vitamin D status is associated with bone mineral density in adolescents: findings from the Korea National Health and Nutrition Examination Survey. Nutr Res. 2021;87:13–21. https://doi.org/10.1016/j.nutres.2020.12.011.
54. Constable AM, Vlachopoulos D, Barker AR, Moore SA, Soininen S, Haapala EA, et al. The independent and interactive associations of physical activity intensity and vitamin D status with bone mineral density in prepubertal children: the PANIC Study. Osteoporos Int. 2021;32:1609–20. https://doi.org/10.1007/s00198-021-05872-z.
55. Jastrzębska J, Skalska M, Radzimiński Ł, Niewiadomska A, Myśliwiec A, López-Sánchez GF, et al. Seasonal changes in 25(OH)D concentration in young soccer players—implication for bone resorption markers and physical performance. Int J Environ Res Public Health. 2021;18:2932. https://doi.org/10.3390/ijerph18062932.
56. Jastrzębska J, Skalska M, Radzimiński Ł, López-Sánchez GF, Weiss K, Hill L, et al. Changes of 25(OH)D concentration, bone resorption markers and physical performance as an effect of sun exposure, supplementation of vitamin D and lockdown among young soccer players during a one-year training season. Nutrients. 2022;14:521. https://doi.org/10.3390/nu14030521.
57. Yang G, Lee WYW, Hung ALH, Tang MF, Li X, Kong APS, et al. Association of serum 25(OH)Vit-D levels with risk of pediatric fractures: a systematic review and meta-analysis. Osteoporos Int. 2021;32:1287–300. https://doi.org/10.1007/s00198-020-05814-1.
58. Otis CL, Drinkwater B, Johnson M, Loucks A, Wilmore J. American College of Sports Medicine position stand. The female athlete triad. Med Sci Sports Exerc 1997;29:i–ix. https://doi.org/10.1097/00005768-199705000-00037.
59. Logue DM, Madigan SM, Melin A, Delahunt E, Heinen M, Donnell S-JM, et al. Low energy availability in athletes 2020: an

updated narrative review of prevalence, risk, within-day energy balance, knowledge, and impact on sports performance. Nutrients 2020;12:835. https://doi.org/10.3390/nu12030835.
60. Maya J, Misra M. The female athlete triad: review of current literature. Curr Opin Endocrinol Diabetes Obes. 2022;29:44–51. https://doi.org/10.1097/MED.0000000000000690.
61. Mountjoy M, Sundgot-Borgen JK, Burke LM, Ackerman KE, Blauwet C, Constantini N, et al. IOC consensus statement on relative energy deficiency in sport (RED-S): 2018 update. Br J Sports Med. 2018;52:687–97. https://doi.org/10.1136/bjsports-2018-099193.
62. Singhal V, Reyes KC, Pfister B, Ackerman K, Slattery M, Cooper K, et al. Bone accrual in oligo-amenorrheic athletes, eumenorrheic athletes and non-athletes. Bone. 2019;120:305–13. https://doi.org/10.1016/j.bone.2018.05.010.
63. Christo K, Prabhakaran R, Lamparello B, Cord J, Miller KK, Goldstein MA, et al. Bone metabolism in adolescent athletes with amenorrhea, athletes with eumenorrhea, and control subjects. Pediatrics. 2008;121:1127–36. https://doi.org/10.1542/peds.2007-2392.
64. Ackerman KE, Nazem T, Chapko D, Russell M, Mendes N, Taylor AP, et al. Bone microarchitecture is impaired in adolescent amenorrheic athletes compared with eumenorrheic athletes and nonathletic controls. J Clin Endocrinol Metab. 2011;96:3123–33. https://doi.org/10.1210/jc.2011-1614.
65. Ducher G, Eser P, Hill B, Bass S. History of amenorrhoea compromises some of the exercise-induced benefits in cortical and trabecular bone in the peripheral and axial skeleton: a study in retired elite gymnasts. Bone. 2009;45:760–7. https://doi.org/10.1016/j.bone.2009.06.021.
66. Gordon CM, Ackerman KE, Berga SL, Kaplan JR, Mastorakos G, Misra M, et al. Functional hypothalamic amenorrhea: an Endocrine Society clinical practice guideline. Int J Clin Endocrinol Metab. 2017;102:1413–39. https://doi.org/10.1210/jc.2017-00131.
67. Desbrow B, McCormack J, Burke LM, Cox GR, Fallon K, Hislop M, et al. Sports Dietitians Australia position statement: sports nutrition for the adolescent athlete. Int J Sport Nutr Exerc Metab. 2014;24:570–84. https://doi.org/10.1123/ijsnem.2014-0031.
68. Liu SL, Lebrun CM. Effect of oral contraceptives and hormone replacement therapy on bone mineral density in premenopausal and perimenopausal women: a systematic review. Br J Sports Med. 2006;40:11–24. https://doi.org/10.1136/bjsm.2005.020065.
69. Ackerman KE, Singhal V, Baskaran C, Slattery M, Reyes KJC, Toth A, et al. Oestrogen replacement improves bone mineral density in oligo-amenorrhoeic athletes: a randomised clinical trial. Br J Sports Med. 2019;53:229–36. https://doi.org/10.1136/bjsports-2018-099723.
70. Ackerman KE, Singhal V, Slattery M, Eddy KT, Bouxsein ML, Lee H, et al. Effects of estrogen replacement on bone geometry and microarchitecture in adolescent and young adult oligoamenorrheic athletes: a randomized trial. J Bone Miner Res. 2020;35:248–60. https://doi.org/10.1002/jbmr.3887.
71. Singhal V, Ackerman KE, Bose A, Flores LPT, Lee H, Misra M. Impact of route of estrogen administration on bone turnover markers in oligoamenorrheic athletes and its mediators. J Clin Endocrinol Metab. 2019;104:1449–58. https://doi.org/10.1210/jc.2018-02143.
72. De Souza MJ, Koltun KJ, Williams NI. The role of energy availability in reproductive function in the female athlete triad and extension of its effects to men: an initial working model of a similar syndrome in male athletes. Sports Med. 2019;49:125–37. https://doi.org/10.1007/s40279-019-01217-3.
73. Fredericson M, Kussman A, Misra M, Barrack MT, De Souza MJ, Kraus E, et al. The male athlete triad-a consensus statement from the Female and Male Athlete Triad Coalition part II: diagnosis, treatment, and return-to-play. Clin J Sport Med. 2021;31:349–66. https://doi.org/10.1097/JSM.0000000000000948.
74. Cherian KS, Sainoji A, Nagalla B, Yagnambhatt VR. Energy balance coexists with disproportionate macronutrient consumption across pretraining, during training, and posttraining among Indian junior soccer players. Pediatr Exerc Sci. 2018;30:506–15. https://doi.org/10.1123/pes.2017-0276.
75. Koehler K, Achtzehn S, Braun H, Mester J, Schaenzer W. Comparison of self-reported energy availability and metabolic hormones to assess adequacy of dietary energy intake in young elite athletes. Appl Physiol Nutr Metab. 2013;38:725–33. https://doi.org/10.1139/apnm-2012-0373.
76. Tenforde AS, Fredericson M, Sayres LC, Cutti P, Sainani KL. Identifying sex-specific risk factors for low bone mineral density in adolescent runners. Am J Sports Med. 2015;43:1494–504. https://doi.org/10.1177/0363546515572142.
77. Barrack MT, Fredericson M, Tenforde AS, Nattiv A. Evidence of a cumulative effect for risk factors predicting low bone mass among male adolescent athletes. Br J Sports Med. 2017;51:200–5. https://doi.org/10.1136/bjsports-2016-096698.
78. Kraus E, Tenforde AS, Nattiv A, Sainani KL, Kussman A, Deakins-Roche M, et al. Bone stress injuries in male distance runners: higher modified Female Athlete Triad Cumulative Risk Assessment scores predict increased rates of injury. Br J Sports Med. 2019;53:237–42. https://doi.org/10.1136/bjsports-2018-099861.
79. Baim S, Leonard MB, Bianchi M-L, Hans DB, Kalkwarf HJ, Langman CB, et al. Official positions of the International Society for Clinical Densitometry and executive summary of the 2007 ISCD Pediatric Position Development Conference. J Clin Densitom. 2008;11:6–21. https://doi.org/10.1016/j.jocd.2007.12.002.
80. Mountjoy M, Sundgot-Borgen J, Burke L, Carter S, Constantini N, Lebrun C, et al. The IOC consensus statement: beyond the Female Athlete Triad—Relative Energy Deficiency in Sport (RED-S). Br J Sports Med. 2014;48:491–7. https://doi.org/10.1136/bjsports-2014-093502.