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Update on Preventing Overuse Injuries in Youth Athletes

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Abstract

Purpose of Review To describe different sports-specific and generalized strategies for prevention of overuse injuries in the youth athlete, and additionally, to review recent discussions of early sport specialization as it relates to pediatric and adolescent overuse injuries.

Recent Findings Youth athletes are at an increased risk for developing overuse injuries due to their immature nervous and musculoskeletal systems and conditions unique to youth sports. Risk factors can be intrinsic or extrinsic to the athlete, and modified by sport or non-sport factors. Critical to preventing overuse injuries is attention to rates of load in training and recovery. Despite evidence against early sport specialization, it remains unclear whether youth specialization is an independent risk factor driving negative outcomes including overuse injuries, or whether it is the associated training loads and conditions.

Summary In order to provide evidence-based and sport-specific guidelines to preventing overuse injuries, we are in need of more robust, specific, and prospective studies.

Keywords Overuse injuries · Early specialization · Youth athletes · Growth plate injuries · Load management · Injury prevention

Introduction

Overuse injuries occur when there are cycles of excessive loading and/or inadequate recovery [1•, 2•, 3]. They may be sports-specific, preceded by a period of subclinical tissue damage where the athlete may be asymptomatic [3], occur with minor or trivial trauma, and result in disproportionate symptoms and consequences [4]. Overuse injuries have been documented as more common than acute traumatic injuries and commonly occur at the physes, joints, bones, and apophyses [1•]. Complications may include physeal widening, premature closure of growth plates, growth arrest, inappropriate ossification, and avulsion fractures [5, 6] not to mention time away from sport and impacts on quality of life.

Youth athletes have immature musculoskeletal systems including weak chondro-osseous junctions, decreased muscle mass, and decreased bone mineral content that can make them uniquely prone to certain overuse injuries [6]. Additionally, they are adapting to their rapidly changing physiologic height [7], developing their movement patterns [8], and their training may not be developmentally appropriate [4, 7, 9]. A rapid increase in training with limited recovery in poorly conditioned tissue and lack of appropriate sport training or oversight for their age also puts youth athletes at risk for overuse injuries. These injuries may go undetected for long periods of time due to decreased autonomy and the inability to provide a good history. Thus, special attention to evidence-based monitoring, training, and rehabilitation for this population is critical to preventing overuse injuries and developing healthy, capable, and resilient young athletes [10].

Currently, there is literature describing rehabilitation after many injuries in the pediatric and adolescent athlete, but limited literature describes prevention of overuse injuries.

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In this review, we aim to describe different sports-specific and generalized strategies for prevention of overuse injuries in the pediatric and adolescent athlete. We also provide a review of recent discussions of early sport specialization as it relates to pediatric overuse injuries.

Common Pediatric and Adolescent Overuse Injuries

Apophyseal Injuries

Apophysitis and other apophyseal injuries are common in the pediatric and adolescent population. Athletes are at risk for these injuries when bone length outpaces muscle tendon unit growth and results in large increases in tension at the apophysis with physical activity and sports [11]. Osgood-Schlatter disease and Sinding-Larsen-Johansson disease are examples of apophysitis' at the knee (at the tibial tuberosity and distal patellar pole, respectively) and are common in sports that involve repetitive jumping/landing, sprinting, and high impact and tension across the knee extensor mechanism [1•, 4, 12]. We also commonly see apophysitis at the medial epicondyle in the form of "Little Leaguer's Elbow," at the heel in Sever's disease, at open growth plates at the hip and pelvis, and at the spinous processes [2•]. Children can essentially develop apophysitis' at any open secondary ossification center. These apophysitis' generally have favorable outcomes and resolve when the growth plates are close, but can persist through adolescence [13•]. Treatment typically involves stretching, rest, icing, NSAIDs, cross-training, and improving flexibility and biomechanics [1•, 11, 13•]. Chronic apophysitis can be treated conservatively with bracing, casting, and significant rest time. However, avulsion fractures may need to be treated surgically if there is significant displacement [1•, 2•, 13•, 14, 15].

Strategies to prevent apophyseal injuries typically involve modification or reduction in training load, cross-training/diversification of training, and potentially avoiding early sports specialization. Prevention is difficult due to the susceptibility of the cartilaginous growth plate to repetitive physical loading and mechanical stresses that occur with many sports activities. The cartilage is the weakest part of the kinetic chain and the most commonly injured in the adolescent. Growth spurts can cause an imbalance in strength and flexibility, and young athletes will be prone to injury during sudden overloads of exercises. Additionally, during rapid growth (approximately 8 cm/year in females and 9 cm/year in males [16], there is a transient deficit in bone mineralization which can make the growth plates even weaker. Thus, short periods of rest and exercise programs of muscle conditioning and stretching are recommended as well as reduction in training loads during rapid growth periods [11]. Caregivers should measure heights every 3 months and young athletes should avoid repetitive movements without rest. Coaches and athletes should be notified that the quality of workouts is more important than training volume. Equipment such as heel cups, patellar tendon straps, and appropriate shoewear can be considered to treat apophysitis pain and to address biomechanics [1•, 2•, 13•, 14, 15]. Finally, there should be periodization of training applied to athletic and sports training plans to avoid training overload [11].

Physeal Injuries

Physeal injuries are injuries of the epiphyseal growth plates on long bones, which are vulnerable during adolescence. Growth plate cartilage is less resistant to stress than adult articular cartilage and the physis may be 2–5 times weaker than the surrounding tissue [4, 17]. Repetitive impact forces applied across an open growth plate may result in growth plate widening and edema, and if the growth plates are repetitively injured, this can result in early bridging and premature closure of the epiphysis. If early closure of the epiphysis occurs, this halts their growth and can potentially cause irreversible deformities in children. Common sports related physeal injuries include proximal humerus epiphysis injury known as "little leaguer's shoulder", and distal radius epiphysis injury also known as "gymnast's wrist" [1•, 2•, 4, 18, 19]. Other sports physeal injuries that have been reported include distal humerus injuries in young baseball players and middle phalanx of the fingers in young sport climbers [20–23]. Repetitive loading, high duration, and high intensity of sport training have been reported to be associated with these injuries [20, 23].

Treatment for mild or moderate cases of physeal injuries involves rest from the offending loading and impact. Recognizing and intervening early is important to prevent severe cases of premature growth plate closure. If severe injury has occurred and there is premature epiphyseal closure, the contralateral limb, or in the case of distal radius closure, the paired ulna, must be monitored to determine if artificial closure is necessary to avoid deformities and preserve functionality [19]. Prevention of physeal injuries therefore involves monitoring and modifying the cumulative load of stresses across the growth plates [4, 18]. Different strategies have arisen to help avoid this overuse injury including endorsing good sport movement biomechanics with athletic training, physical therapy, good coaching, and sporting organization interventions such as pitch count limits in baseball, monitoring for decreased throwing velocity, and potential recommendations of avoiding early sports specialization [2•, 24–26].

Stress Injuries and Other Bony Injuries

Bony stress injuries are also commonly seen in youth and adolescent athletes. These may take the form of stress edema, stress reactions, stress fractures, osteochondritis dissecans lesions, or other avascular necrosis pathologies. Stress fractures can take place in the lumbar spine, femur, tibia, distal radius, and other bony areas. They are caused by repetitive submaximal stress on bones, and are seen across the spectrum of many sports such as runners, soccer players, figure skaters, dancers, baseball players, and football players [9, 27, 28]. They are increasing in prevalence overall and females appear to be more prone than males in sustaining these injuries [29–31]. Stress injuries occur due to increased load relative to the strength of the bony cortex and trabecular bone. Bone mineralization trails linear bone growth and may result in transient lower bone density and strength as youth athletes are growing and developing [24]. Prevention strategies involve appropriate core and extremity strengthening, neuromuscular control, flexibility, gradual increase in training level, appropriate equipment, and good bone health [1•, 32, 33].

Though weight bearing is important to improve bone mineral density (BMD) and it is important to start young to help build up bone mass, certain populations such as gymnasts, dancers, figure skaters, and other esthetic forward or weight class-based sports may be prone to the Female Athlete Triad or Relative Energy Deficiency in Sport (RED-S). Adolescents with RED-S have decreased energy availability which can lead to menstrual dysfunction, sex hormone deficiencies, and poor bone health. It is more difficult to assess in prepubescent athletes due to their lack of menarche or spermarche. These children should be monitored for appropriate nutrition, growth milestones, electrolyte status, and delayed onset of puberty. RED-S can be associated with a higher prevalence of stress injuries and must be evaluated for and treated with rest, close monitoring, and improvement in nutrition [29–31]. Those who are oligo-amenorrheic lack much of the bone health benefits of weight bearing exercise, and in this population, weight bearing may in fact increase stress fracture risk [34, 35].

Physical activity is a great contributor to bone mass, and children should have a goal for at least 1 h daily, with bone and muscle strengthening 3 days per week [35, 36]. High-impact and multidirectional loading can assist as well, though balanced to avoid excessive loading [37, 38•]. Ball sport participation has been shown to improve bone mass as well, likely due to multidirectional loading. Athletes can consider ball sports or other multidirectional loading sports participation, neuromuscular training, and early activity to improve bone mass and prevent future osteoporosis [35, 39, 40]. Overall bone health can be maintained through physical activity, and athletes are generally at less risk of low BMD in the future. Vitamin D and calcium intake must be monitored and supplementation considered if daily intake in food is insufficient [38•, 41]. Vitamin D status can be measured through serum-25 hydroxyvitamin D, and 400 IU of supplemental vitamin D can be provided to adolescents with low levels, with the potential for higher doses as needed [36]. Adolescents require up to 1300 mg of calcium daily [37]. Unfortunately, while many such athletes are at risk of stress injuries (one study demonstrated 60% overall) [38•], there is limited knowledge within this population about their exact susceptibility [38•].

Osteochondritis dissecans (OCD) is a disorder of the subchondral bone and overlying articular cartilage [4]. Though no known cause is identifiable, it is hypothesized that repetitive loading and injury may lead to the development of the OCD lesions [4]. These injuries commonly occur in the knees in soccer and basketball players, in the elbow in pitchers and baseball players and gymnasts, and in the ankles in gymnasts (though it does not always occur following these exact demographic patterns) [1•, 4, 39, 40]. Diagnosis involves radiographs and MRI of the joints to identify and classify the lesions [39]. Treatment often includes non-weight bearing status for several weeks to months, immobilization at times, and progressive return to activity [1•]. Surgery may be required for unstable or non-healing lesions [41, 42]. Prevention involves focus on upper and lower extremity flexibility and core strengthening, and a reduction in activities that involve excessive impact/stress across the joints [43–45].

There are also a number of avascular necrosis pathologies associated with youth sport athletes such as Kienbocks disease in those with significant wrist use and Freiberg's infraction in girls age 12–15 with collapse of the second metatarsal [1•]. Treatment and prevention strategies are similar to those described above for stress injuries and OCD lesions.

Load and Overuse Injuries

Load and Injury Risk

Load is defined as "the sport and non-sport burden (single or multiple physiological, psychological or mechanical stressors) as stimulus that is applied to a human biological system (including subcellular elements, a single cell, tissues, one or multiple organ systems, or the individual)" [3]. A 2016 consensus statement on load and risk of injury by the International Olympic Committee reviews how training that leads to improvements in performance and fitness stimulates homeostatic responses and adaptations; however, injury results when the load outweighs tissue capacity [3]. The relationship between load and injury is mediated by intrinsic and extrinsic factors, as well as psychological and non-sport stressors [3, 10].

In 2020, researchers pointed out that when quantifying load and overuse injuries, it is important to measure not only absolute load (cross-sectional measurement of load), but also load rate and load history [46•]. High absolute load in the accustomed athlete has been shown to be protective in certain sports against injury [46•]. Non-contact injuries (such as overuse injuries) are often associated with excessive fluctuations in load rate (intensity, duration, frequency) within the training program. Gabbett developed a model for describing training load as a ratio between acute (training load in last week) and chronic (training load in last 28 days) load, and found the optimal ratio in a training program of acute to chronic load is 0.8–1.3, which reflects gradual < 10% increases and decreases in load, to reduce players injury risk [47].

Competitions have been found to place a higher load on athletes than training, and competition calendar congestion has been identified as a risk factor for injuries. In soccer, 2 matches per week with less than 4 days to recover in between compared to 1 match per week have been associated with increased injury risk [48]. More sport-specific guidelines for training and competition are needed.

Monitoring and Quantifying Load, Injury, and Well-being

Monitoring conditions and athlete behavior is key to understanding the relationship between load and injury, but monitoring training responses is also important for ensuring therapeutic doses of load. The International Olympic Committee reviewed a multitude of measurement tools for monitoring external and internal load and injury [3]. As pointed out in their statement, the inherent challenge to monitoring for overuse injuries is that the injuries may be preceded by a period of subclinical tissue damage where the athlete may be asymptomatic. This underlines the importance of prospective monitoring of injuries which includes sensitive measures for preclinical symptoms such as soreness and pain, recording prevalence (not just incidence), and classifying injury based on functional level rather than simply time away from sport. Novel approaches including apps for administering, tracking, and interpreting these measures have been emerging. Translating to real-world use involves balancing effective and sensitive measures while not imposing an unrealistic burden on coaches and athletes. Studies so far using novel tracking methods have shown that overuse injuries are just as much a problem as acute injuries in sports, despite their underrepresentation in the literature [49, 50, 51•].

Prevention Strategies for Overuse Injuries

Risk factors for overuse injuries can be intrinsic or extrinsic. Intrinsic factors include rate of growth, development, strength, cardiopulmonary compromise, maturity, bone health, and previous injury. Extrinsic factors include too rapid training increases, sudden changes in equipment or training styles (e.g., running surfaces and shoe ware changes), minor skeletal asymmetries, limited muscular flexibility, and poor core stability [1•, 52, 53]. In athletes who develop pain attributed to an overuse injury, they should rest and limit the frequency and duration of training, avoid painful exercises, address biomechanical inefficiencies, and alter any inappropriate equipment [1•, 52, 53]. If the symptoms do not improve quickly over 1–2 weeks, they should be evaluated by a pediatric sports or musculoskeletal specialist.

Furthermore, caregivers should track overall development. In addition to an annual exam, BMI, signs of disordered eating, menstruation, hydration, and sleep schedule should be monitored. Sports where athletes must "make weight" may require even closer monitoring [5]. Proper footwear, forgiving running surfaces, cross-training, and appropriate equipment are important for athlete health and safety as well [54•].

Finally, health literacy for athletes including musculotendinous imbalances, anatomic alignments, overall fitness, flexibility, and education about gradual increases in training load should be provided. Injuries should be taken seriously and athletes should not be encouraged to play through pain [4, 6, 55].

Prevention, Training, and Rehabilitation

While protocols for preventing youth athlete acute injuries, such as ACL injuries, are widely explored in the literature, specific prevention protocols for preventing overuse injuries are less discussed. Based on our understanding of athlete variability in the pathogenesis of overuse injuries, load from training and competitions should be flexible and allow for inter- and intra-athlete variation and circumstances [10, 60•, 61]. While not all psychological loads which contribute to injury risk are modifiable, it is important for athletes, their parents, and coaches to be aware of them and consider adjusting training schedules accordingly during times of higher stress.

When designing rehabilitation from an injury to return to play, "practitioners should consider and plan the appropriate amount of time required to progress from the floor (eg, rehabilitation) to the ceiling (eg, return to performance)" which allows athletes to safely progress to the ceiling while reducing injury risk and enhancing performance [10]. This is going to vary based on the athlete's history, condition, injury, and sport-specific requirements and goals.

Early Sport Specialization and Overuse Injuries

Overview

There has been growing concern due to associations between early sport specialization and negative outcomes in youth athletes, including overuse injuries relevant for this review, which has led to multiple organizations and authorities to publish position statements recommending against early specialization.

A 2021 narrative review of early sport specialization synthesized existing literature and evidence from sports psychology, sports medicine, and human development into a framework for practitioners working with adolescent athletes to better understand conditions, possible mechanisms, and prevention strategies for associated negative outcomes (Fig. 1) [56•].

The trend for youth athletes to specialize early has been increasing out of the belief that it will improve performance outcomes, due to pressures to become an elite athlete [57], and the professionalization of youth sport [58, 59, 60•]. The need for early specialization has been challenged as studies have found that early sport specialization may not be a requirement to become an elite athlete [60•, 61–64]. Additionally, elite athletes have actually been found to specialize later than their semi-elite peers (14 years old, compared to < 12 years old), and youth specialization has not been shown to improve task-related performance measures in certain sports [65]. Notable exceptions are women's figure skating and gymnastics as peak performance may often occur before puberty, requiring early specialization to achieve elite status [60•].

Defining Specialization and Early Specialization

One of the challenges in drawing conclusions from the literature on early sport specialization is the lack of a consistent definition across studies [66]. In an effort to use a scientific process to arrive at a consensus for the definition of youth specialization in sports, a multidisciplinary group of experts in the field employed the Delphi method and concluded in their 2021 statement, "Sport specialization is intentional and focused participation in a single sport for a majority of the year that restricts opportunities for engagement in other sports and activities." [67].

A common scale used in the literature to measure sport specialization is Jayanthi's 2013 and 2015 Sport Specialization Scale [53, 68] which classifies athletes' specialization into low, moderate, or high. The 2013 version consists of a 3-item scale (which has since been updated to a 6-item scale). The 3-item scale is as follows: (1) single sport training, (2) exclusion of other sports, (3) year round training (> 8 months). Critiques of this scale have included the following, "a recreational athlete who participates once a week for 2 h in basketball, but quit soccer at age seven, would be regarded as more specialized than a competitive basketball player who participates for 6 h a week but only ever participated in basketball, despite

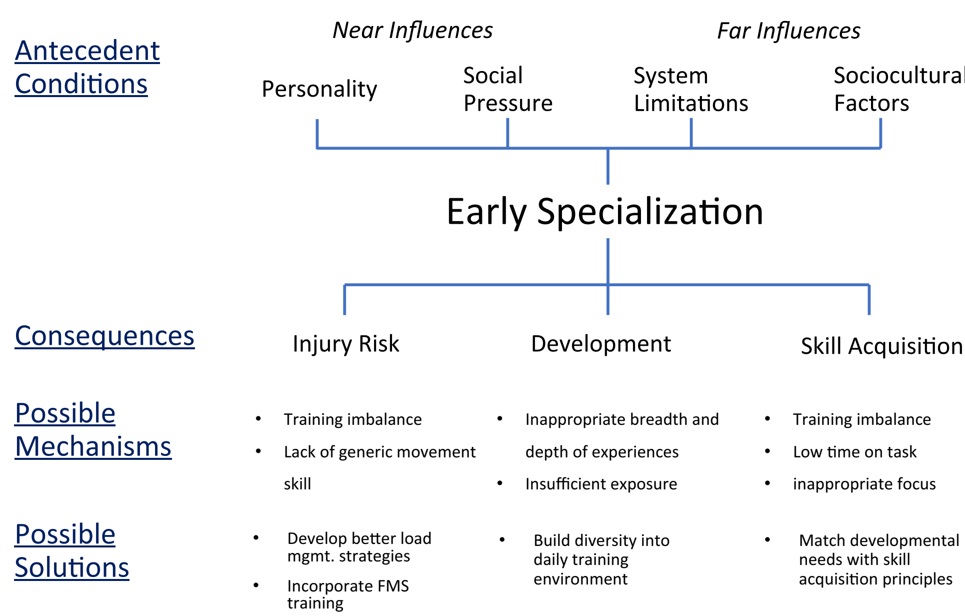

Fig. 1 A framework for exploring early specialization in sport. Fundamental movement skills (FMS) are the basic building blocks of advanced movement that occurs later in athlete development [56•]

the fact that most practitioners would be more concerned about the latter" [60•].

The definition of "early," as it pertains to early sport specialization, has also been found to be inconsistent across the literature, ranging from < 12 to 23 years old [52]. While chronologic age varies across the literature, many agree that specializing in the prepubescent and early pubescent and period should be avoided and delayed until around 15–16 years old [54•, 63,64]. The developmental approach to training recognizes the inherent vulnerabilities of training during adolescence due to an interplay between "the properties of the musculoskeletal system, the influence of pubertal hormones, and the lag time between physical and cognitive development" [9]. Age has been found to be more predictive than sports specialization alone of safe movement patterns in youth, which are key to injury prevention [8]. Classifying athletes by their biologic age (skeletal age, sexual age, age at menarche) rather than their chronologic age and monitoring for times of rapid growth (via peak height velocity) has been suggested as a means to guide and adjust training load during times of particular physiologic vulnerability [69].

Evidence on Early Specialization and Overuse Injuries

Specialization has been found to be associated with higher rates of overuse injury in young athletes across multiple studies [57, 65, 77•]. Despite the series of studies published on the association between early specialization and overuse injuries, recently, there have also been critiques of this evidence on multiple grounds. A 2020 systematic review recently found that the majority of literature on the topic consists of "non-data driven, commentaries, and reviews which undermines the extent to which recommendations about early specialization can be seen as evidence-based" [66, 72]. This has placed practitioners in a position where they are "warned to advise parents and athletes against the practice of specialization without understanding *why* or *how* it should be avoided" [62]. Additionally, most studies are retrospective or cross-sectional and there are few prospective and sport-specific studies [62, 66]. Overall, the existing research has been described to "suffer from numerous methodological limitations and the research field needs direction" [66].

Sport Sampling

The counter to sport specializing has been described as "sport sampling," and youth athlete sport samplers have been found to have decreased risk of sports injury when compared with those who specialize in one sport [70]. Thus, in many of the consensus statements advising against early sport specialization, they have promoted sport sampling. A limitation to promoting sampling over specializing which has been identified by reviewers of the literature is that few of the studies examining the relationship between specialization and injury risk controlled for training load [65]. Thus, it remains unclear whether youth specialization is an independent risk factor driving negative outcomes including overuse injuries, or whether it is the associated training loads and conditions [71].

Overall, due to methodological weaknesses in the evidence, we cannot infer at this point that sport samplers appear to be protected against injuries simply because they are participating in multiple sports. Perhaps samplers who achieve elite status or avoid injury are more athletic and have superior motor learning and control? Perhaps those who are more athletic are drawn to participate in more sports [60•]? As future research and guidelines are developed, it is imperative for them to be sport-specific, as there are certain sports such as team-ball sports where skills may cross-over between sports and athlete's performance and motor skills may benefit from delaying specialization [72], whereas in sports which require athletes to specialize earlier for elite status (or in the athletes who choose to specialize early), mitigating risk must occur through evidence-based and individualized training [60•, 73].

Guidance for Managing Load for the Specialized Athlete

For the specialized athlete, experts have recently proposed prescribing appropriate load (for both optimizing performance and reducing injury risk) based on classifying them into one of three theoretical types of youth athletes: the load-tolerant athlete, the load-naive athlete, the load-sensitive athlete [73]. The load-tolerant youth athletes are skeletally mature and experienced in high and intense loads in specialized training. Load-naive youth athletes are skeletally immature and/or have not been exposed to intense and specialized training loads. The load-sensitive youth athletes are either (a) skeletally immature or (b) skeletally mature and have experienced injury or recurrent injury associated with training load progressions. Borrowing from peak performance research in early sport specialization for football [74], this model defines the "floor as the athlete's current capacity; and ceiling [as] their potential capacity to perform without injury" [73]. For the athletes who do choose to specialize, this framework offers a supportive guide which accounts for variety amongst the athletes and across different phases of development, capacity, and performance.

Future Directions for Research

In order to better understand the actual consequences of early specialization and thus guide prevention of the negative associated outcomes, the field must seek to better understand the "effect of specialization on motor control development, sport performance, musculoskeletal injury risk, psychosocial outcomes, burnout and attrition and on optimal strategies for youth athlete training and development in specific sports" [56•].

Additionally, research into sport-specific and population-specific prevention of each of the aforementioned types of overuse injuries including in children who do not have early specialization needs to be addressed [1•]. Assessing risk factors for youth athletes at risk for overuse injury prior to each sporting season will be helpful to mitigate training load over the full season. These may include biomarkers, radiographic or ultrasound markers, or demographics that will assist caregiver, coach, and trainer knowledge of these youth athletes' risk [6]. Prospective, cohort-based, and sport-specific studies guided towards establishing consistent, valid, and reliable measures for screening, monitoring, and guiding training to reduce risk of overuse injuries in youth athletes are necessary to enable caregivers to provide evidence-based guidance [60•]. Additionally, follow-up research on dissemination and implementation is necessary to ensure that guidelines and measures do not place an impractical burden on athletes and coaches and can meaningfully be integrated into real-life practice [1•].

Finally, the appropriate education modules for coaches, athletic trainers, and other staff to assess core stability, muscle group strength, and overall biomechanics prior to the start of each season may serve as proxies for these risk factors as well [25, 75].

Conclusion

Common overuse injuries in youth athletes include many physeal and bony stress injuries that are unique to their age and population. Many of the injury prevention strategies involve monitoring, modifications, and limitations in repetitive loading across the various areas of the body and across growth plates. There are several theories about how loading intensity and sports specialization impact overuse injuries and we provided a summary of an updated review on prevention strategies as it relates to these topics.

Despite the evidence against early sports specialization, we are in need of more robust, specific, and prospective studies [60•]. The literature thus far exploring possible mechanisms of negative outcomes and possible solutions reveals the complexity of conditions and variety between individual athletes and sports. This underscores the importance for youth athletes to have health literacy in this area, attentive and knowledgeable coaches and trainers, support teams, and access to medical surveillance.

Declarations

Conflict of Interest The authors declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as: • Of importance

1.• Karlin A, Goyeneche N. Sport-specific musculoskeletal injuries. In: Pediatric Rehabilitation: Principles and Practice. 6th ed. New York: Springer Publishing Company; 2021. p. 260–79. **Description of different types of overuse injuries based on mechanism of injury and sport**.
2.• Ridenour R, Hennrikus W. Overuse injuries in pediatric athletes. Adv Pediatr. 2020;67:171–82. https://doi.org/10.1016/j.yapd.2020.04.001. **Description of overuse injuries in adolescent athletes**.
3. Soligard T, Schwellnus M, Alonso JM, 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(17):1030–41.
4. Kerssemakers SP, Fotiadou AN, de Jonge MC, Karantanas AH, Maas M. Sport injuries in the paediatric and adolescent patient: a growing problem. Pediatr Radiol. 2009;39(5):471–84.
5. Bernstein K, Seales P, Mroszczyk-McDonald A. Selected musculoskeletal issues in adolescents. Prim Care. 2020;47(2):257–71.
6. Bedoya MA, Jaramillo D, Chauvin NA. Overuse injuries in children. Top Magn Reson Imaging. 2015;24(2):67–81.
7. McKay D, Broderick C, Steinbeck K. The adolescent athlete: a developmental approach to injury risk. Pediatr Exerc Sci. 2016;28(4):488–500.
8. Heath MR, Janosky JJ, Pegno A, Schachne JM, Fabricant PD. Age is more predictive of safe movement patterns than are physical activity or sports specialization: a prospective motion analysis study of young athletes. Am J Sports Med. 2021;49(7):1904–11.
9. Jaimes C, Jimenez M, Shabshin N, Laor T, Jaramillo D. Taking the stress out of evaluating stress injuries in children. Radiogr Rev Publ Radiol Soc N Am Inc. 2012;32(2):537–55.
10. Bergeron MF, Mountjoy M, Armstrong N, Chia M, Côté J, Emery CA, et al. International Olympic Committee consensus statement on youth athletic development. Br J Sports Med. 2015;49(13):843–51.
11. Longo UG, Ciuffreda M, Locher J, Maffulli N, Denaro V. Apophyseal injuries in children's and youth sports. Br Med Bull. 2016;120(1):139–59.
12. Pai DR, Strouse PJ. MRI of the pediatric knee. AJR Am J Roentgenol. 2011;196(5):1019–27.
13.• Achar S. Apophysitis and Osteochondrosis: Common causes of pain in growing bones - American Family Physician [Internet]. 2019 [cited 2022 Feb 12]. Available from: https://www.aafp.org/afp/2019/0515/p610.html. **Description of apophysitis injuries**.
14. Ramponi DR, Baker C. Sever's disease (calcaneal apophysitis). Adv Emerg Nurs J. 2019;41(1):10–4.
15. Wu M, Fallon R, Heyworth BE. Overuse injuries in the pediatric population. Sports Med Arthrosc Rev. 2016;24(4):150–8.

16. Reese J. What is a growth spurt during puberty? [Internet]. 2020 [cited 2022 Jun 26]. Available from: https://www.hopkinsallchildrens.org/ACH-News/General-News/What-is-a-Growth-Spurt-During-Puberty.
17. Larson RL, McMahan RO. The epiphyses and the childhood athlete. JAMA. 1966;196(7):607–12.
18. Emery KH. Imaging of sports injuries of the upper extremity in children. Clin Sports Med. 2006;25(3):543–68, viii.
19. Chang CY, Shih C, Penn IW, Tiu CM, Chang T, Wu JJ. Wrist injuries in adolescent gymnasts of a Chinese opera school: radiographic survey. Radiology [Internet]. 1995 Jun 1 [cited 2022 Feb 21]; Available from: https://pubs.rsna.org/doi/abs/10.1148/radiology.195.3.7754022.
20. Caine D, DiFiori J, Maffulli N. Physeal injuries in children's and youth sports: reasons for concern? Br J Sports Med. 2006;40(9):749–60.
21. Podesta L, Sherman MF, Bonamo JR. Distal humeral epiphyseal separation in a young athlete: a case report. Arch Phys Med Rehabil. 1993;74(11):1216–8.
22. Schöffl V, Hochholzer T, Winkelmann HP, Strecker W. Pulley injuries in rock climbers. Wilderness Environ Med. 2003;14(2):94–100.
23. Ogden JA. Skeletal Injury in the Child [Internet]. 3rd ed. New York, NY: Springer Publishing Company; 2000 [cited 2022 May 26]. 1198 p. Available from: https://link.springer.com/book/10.1007/b97655.
24. Andrews JR, Wilcox CL. Decision making in the throwing athlete. Sports Med Arthrosc Rev. 2014;22(2):130–6.
25. Richardson BM, Masquelin ME. Common pediatric musculoskeletal issues. Prim Care. 2021;48(3):417–28.
26. Arnold A, Thigpen CA, Beattie PF, Kissenberth MJ, Shanley E. Overuse physeal injuries in youth athletes. Sports Health. 2017;9(2):139–47.
27. DeFranco MJ, Recht M, Schils J, Parker RD. Stress fractures of the femur in athletes. Clin Sports Med. 2006;25(1):89–103, ix.
28. Er MS, Eroglu M, Altinel L. Femoral neck stress fracture in children: a case report, up-to-date review, and diagnostic algorithm. J Pediatr Orthop B. 2014;23(2):117–21.
29. Ackerman KE, Cano Sokoloff N, Maffazioli GDN, Clarke H, Lee H, Misra M. Fractures in relation to menstrual status and bone parameters in young athletes. Med Sci Sports Exerc. 2015;47(8):1577–86.
30. Frank RM, Romeo AA, Bush-Joseph CA, Bach BRJ. Injuries to the female athlete in 2017: Part I: General Considerations, Concussions, Stress Fractures, and the Female Athlete Triad. JBJS Rev. 2017;5(10):e4.
31. Patel NM, Mai DH, Ramme AJ, Karamitopoulos MS, Castañeda P, Chu A. Is the incidence of paediatric stress fractures on the rise? Trends in New York State from 2000 to 2015. J Pediatr Orthop B. 2020;29(5):499–504.
32. Sato M, Mase Y, Sairyo K. Active stretching for lower extremity muscle tightness in pediatric patients with lumbar spondylolysis. J Med Investig JMI. 2017;64(1.2):136–9.
33. Donatelli R, Dimond D, Holland M. Sport-specific biomechanics of spinal injuries in the athlete (throwing athletes, rotational sports, and contact-collision sports). Clin Sports Med. 2012;31(3):381–96.
34. Fredericson M, Jennings F, Beaulieu C, Matheson GO. Stress fractures in athletes. Top Magn Reson Imaging. 2006;17(5):309–25.
35. Brukner P, Bradshaw C, Khan KM, White S, Crossley K. Stress fractures: a review of 180 cases. Clin J Sport Med Off J Can Acad Sport Med. 1996;6(2):85–9.
36. Casey CF, Slawson DC, Neal LR. Vitamin D Supplementation in infants, children, and adolescents. Am Fam Physician. 2010;81(6):745–8.
37. Graham L. IOM releases report on dietary reference intakes for calcium and vitamin D. AFP. 2011;83(11):1352.
38.• Tosi M, Maslyanskaya S, Dodson NA, Coupey SM. The female athlete triad: a comparison of knowledge and risk in adolescent and young adult figure skaters, dancers, and runners. J Pediatr Adolesc Gynecol. 2019;32(2):165–9. https://doi.org/10.1016/j.jpag.2018.10.007. **Description of athlete triad and athlete knowledge and risk**.
39. Bradley JP, Petrie RS. Osteochondritis dissecans of the humeral capitellum. Diagnosis and treatment Clin Sports Med. 2001;20(3):565–90.
40. Hale H, Bae DS. Treatment of adolescent osteochondritis dissecans of the capitellum: a systematic review of the literature. :7.
41. McElroy MJ, Riley PM, Tepolt FA, Nasreddine AY, Kocher MS. Catcher's knee: posterior femoral condyle juvenile osteochondritis dissecans in children and adolescents. J Pediatr Orthop. 2018;38(8):410–7.
42. Mihara K, Tsutsui H, Nishinaka N, Yamaguchi K. Nonoperative Treatment for osteochondritis dissecans of the capitellum. Am J Sports Med. 2009;37(2):298–304.
43. Eismann EA, Pettit RJ, Wall EJ, Myer GD. Management strategies for osteochondritis dissecans of the knee in the skeletally immature athlete. J Orthop Sports Phys Ther. 2014;44(9):665–79.
44. Yang JS, Bogunovic L, Wright RW. Nonoperative treatment of osteochondritis dissecans of the knee. Clin Sports Med. 2014;33(2):295–304.
45. Tepolt FA, Kalish LA, Heyworth BE, Kocher MS. Nonoperative treatment of stable juvenile osteochondritis dissecans of the knee: effectiveness of unloader bracing. J Pediatr Orthop B. 2020;29(1):81–9.
46.• Gabbett TJ. How much? how fast? how soon? three simple concepts for progressing training loads to minimize injury risk and enhance performance. J Orthop Sports Phys Ther. 2020;50(10):570–3. https://doi.org/10.2519/jospt.2020.9256. **Guidance on load progrss to reduce injury**.
47. Gabbett TJ. The training—injury prevention paradox: should athletes be training smarter and harder? Br J Sports Med. 2016;50(5):273–80.
48. Dupont G, Nedelec M, McCall A, McCormack D, Berthoin S, Wisløff U. Effect of 2 soccer matches in a week on physical performance and injury rate. Am J Sports Med. 2010;38(9):1752–8.
49. Clarsen B, Myklebust G, Bahr R. Development and validation of a new method for the registration of overuse injuries in sports injury epidemiology: the Oslo Sports Trauma Research Centre (OSTRC) Overuse Injury Questionnaire. Br J Sports Med. 2013;47(8):495–502.
50. Clarsen B, Rønsen O, Myklebust G, Flørenes TW, Bahr R. The Oslo Sports Trauma Research Center questionnaire on health problems: a new approach to prospective monitoring of illness and injury in elite athletes. Br J Sports Med. 2014;48(9):754–60.
51. Clarsen B, Bahr R, Heymans MW, Engedahl M, Midtsundstad G, Rosenlund L, et al. The prevalence and impact of overuse injuries in five Norwegian sports: application of a new surveillance method. Scand J Med Sci Sports. 2015;25(3):323–30.
52. Wen DY. Risk factors for overuse injuries in runners. Curr Sports Med Rep. 2007;6(5):307–13.
53. Jayanthi NA, LaBella CR, Fischer D, Pasulka J, Dugas LR. Sports-specialized intensive training and the risk of injury in young athletes: a clinical case-control study. Am J Sports Med. 2015;43(4):794–801.
54.• Krabak BJ, Tenforde AS, Davis IS, Fredericson M, Harrast MA, d'Hemecourt P, et al. Youth distance running: strategies for training and injury reduction. Curr Sports Med Rep.

2019;18(2):53–9. https://doi.org/10.1249/JSR.0000000000000564. **Prevention of overuse injuries in runners**.
55. Christopher NC, Congeni J. Overuse injuries in the pediatric athlete: evaluation, initial management, and strategies for prevention. Clin Pediatr Emerg Med. 2002;3(2):118–28.
56.• Mosher A, Till K, Fraser-Thomas J, Baker J. Revisiting early sport specialization: what's the problem? Sports Health. 2021;14(1):13–9. https://doi.org/10.1177/19417381211049773. **Critical up to date review of the literature on early sport specialization**.
57. Watchman T, Spencer-Cavaliere N. Times have changed: parent perspectives on children's free play and sport. Psychol Sport Exerc. 2017;32:102–12.
58. Brenner JS. Sports specialization and intensive training in young athletes. Pediatrics. 2016;138(3):e20162148.
59. Fabricant PD, Lakomkin N, Sugimoto D, Tepolt FA, Stracciolini A, Kocher MS. Youth sports specialization and musculoskeletal injury: a systematic review of the literature. Phys Sportsmed. 2016;44(3):257–62.
60.• Kliethermes SA, Marshall SW, LaBella CR, Watson AM, Brenner JS, Nagle KB, et al. Defining a research agenda for youth sport specialisation in the USA: the AMSSM Youth Early Sport Specialization Summit. Br J Sports Med. 2021;55(3):135–43. **Review of the literature to date on early sport specialization and guidance for future research**.
61. Black S, Black K, Dhawan A, Onks C, Seidenberg P, Silvis M. Pediatric sports specialization in elite ice hockey players. Sports Health. 2018;11(1):64–8.
62. Buckley PS, Bishop M, Kane P, Ciccotti MC, Selverian S, Exume D, et al. Early single-sport specialization: a survey of 3090 high school, collegiate, and professional athletes. Orthop J Sports Med. 2017;5(7):2325967117703944.
63. Huxley D, O'Connor D, Larkin P. The pathway to the top: key factors and influences in the development of Australian Olympic and World Championship Track and Field athletes. Int J Sports Sci Coach. 2017;1(12):174795411769473.
64. Ross K. The effect of specialization and level of competition on injury in elite male ice hockey players: : Vol 0, No 0. Phys Sportsmed [Internet]. 2021 [cited 2022 Apr 28]; Available from: https://www-tandfonline-com.ezproxy.cul.columbia.edu/doi/full/10.1080/00913847.2021.1916786.
65. Kliethermes SA, Nagle K, Côté J, Malina RM, Faigenbaum A, Watson A, et al. Impact of youth sports specialisation on career and task-specific athletic performance: a systematic review following the American Medical Society for Sports Medicine (AMSSM) Collaborative Research Network's 2019 Youth Early Sport Specialisation Summit. Br J Sports Med. 2020;54(4):221–30.
66. Mosher A, Fraser-Thomas J, Baker J. What defines early specialization: a systematic review of literature. Front Sports Act Living [Internet]. 2020 [cited 2022 Mar 24];2. Available from: https://www.frontiersin.org/article/10.3389/fspor.2020.596229.
67. Bell DR, Snedden TR, Biese KM, Nelson E, Watson AM, Brooks A, et al. Consensus definition of sport specialization in youth athletes using a Delphi approach. J Athl Train. 2021;56(11):1239–51.
68. Jayanthi N, Pinkham C, Dugas L, Patrick B, Labella C. Sports specialization in young athletes: evidence-based recommendations. Sports Health. 2013;5(3):251–7.
69. Lloyd RS, Oliver JL, Faigenbaum AD, Myer GD, De Ste Croix MBA. Chronological age vs. biological maturation: implications for exercise programming in youth. J Strength Cond Res. 2014;28(5):1454–64.
70. Carder SL, Giusti NE, Vopat LM, Tarakemeh A, Baker J, Vopat BG, et al. The concept of sport sampling versus sport specialization: preventing youth athlete injury: a systematic review and meta-analysis. Am J Sports Med. 2020;48(11):2850–7.
71. Field AE, Tepolt FA, Yang DS, Kocher MS. Injury risk associated with sports specialization and activity volume in youth. Orthop J Sports Med. 2019;7(9):2325967119870124.
72. Abernethy B, Baker J, Côté J. Transfer of pattern recall skills may contribute to the development of sport expertise. Appl Cogn Psychol. 2005;1:19.
73. Jayanthi N, Saffel H, Gabbett T. Training the specialised youth athlete: a supportive classification model to keep them playing. Br J Sports Med. 2021;55(22):1248–9.
74. Sieghartsleitner R, Zuber C, Zibung M, Conzelmann A. "The early specialised bird catches the worm!" – a specialised sampling model in the development of football talents. Front Psychol [Internet]. 2018 [cited 2022 May 12];9. Available from: https://www.frontiersin.org/article/10.3389/fpsyg.2018.00188.
75. Tisano BK, Estes AR. Overuse injuries of the pediatric and adolescent throwing athlete. Med Sci Sports Exerc. 2016;48(10):1898–905.
76.• Jayanthi NA, Post EG, Laury TC, Fabricant PD. Health consequences of youth sport specialization. J Athl Train. 2019;54(10):1040–9. https://doi.org/10.4085/1062-6050-380-18 **Reviews the risks associated with early sport specialization**.
77.• Murphy K, Sobus KML, Moberg-Wolff E, Dubon ME, Pico EL. Musculoskeletal conditions. In: Pediatric rehabilitation: principles and practice. 6th ed. Springer Publishing Company; 2021:371–409. **Description of musculoskeletal conditions in children and adolescents**.