# Developmental Training Model for the Sport Specialized Youth Athlete: A Dynamic Strategy for Individualizing Load-Response During Maturation

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**Context:** Most available data on athletic development training models focus on adult or professional athletes, where increasing workload capacity and performance is a primary goal. Development pathways in youth athletes generally emphasize multisport participation rather than sport specialization to optimize motor skill acquisition and to minimize injury risk. Other models emphasize the need for accumulation of sport- and skill-specific hours to develop elite-level status. Despite recommendations against sport specialization, many youth athletes still specialize and need guidance on training and competition. Medical and sport professionals also recommend progressive, gradual increases in workloads to enhance resilience to the demands of high-level competition. There is no accepted model of risk stratification and return to play for training a specialized youth athlete through periods of injury and maturation. In this review, we present individualized training models for specialized youth athletes that (1) prioritize performance for healthy, resilient youth athletes and (2) are adaptable through vulnerable maturational periods and injury.

**Evidence Acquisition:** Nonsystematic review with critical appraisal of existing literature.

**Study Design:** Clinical review.

**Level of Evidence:** Level 4.

**Results:** A number of factors must be considered when developing training programs for young athletes: (1) the effect of sport specialization on athlete development and injury, (2) biological maturation, (3) motor and coordination deficits in specialized youth athletes, and (4) workload progressions and response to load.

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**Conclusion:** Load-sensitive athletes with multiple risk factors may need medical evaluation, frequent monitoring, and a program designed to restore local tissue and sport-specific capacity. Load-naive athletes, who are often skeletally immature, will likely benefit from serial monitoring and should train and compete with caution, while load-tolerant athletes may only need occasional monitoring and progress to optimum loads.

**Strength of Recommendation Taxonomy (SORT):** B.

**Keywords:** young athlete; single sport; competition; injury prevention

Historically, participation in sport, including modest amounts of athletic developmental training, has been associated with positive experiences and low injury rates in adolescents.[55] However, youth athletes are now increasingly engaging in higher volumes of sport-specific training at an earlier age. There is also a rise in the number of young athletes aiming to maximize performance-related goals by training and competing in a single sport,[88] with approximately 30% of young athletes highly specialized.[47]

A recent Delphi study defined sport specialization as: ". . . intentional and focused participation in a single sport for a majority of the year that restricts opportunities for engagement in other sports and activities."[5] While there exist little data to support a specific age of early sport specialization, this has been suggested when a young athlete chooses a single sport before the age of 12 years.[49] Early specialization has been estimated in some studies to occur during prepubescent stages with mean ages of 10.4 years in tennis[45] and 9 years in soccer.[26]

Sport specialization has been associated with increased risk for overuse injury and burnout[3,8,36,48,63,85] and with an estimated 60 million children participating in sports, it is now considered a public health issue.[3,48] While many medical and sport organizations recommend against sport specialization prior to middle or late adolescence,[6,11,23,49,52,103] the perception by young athletes and parents that specialization improves athletic performance and long-term athletic career prospects means that while risks of injury and burnout may exist, some are willing to specialize to increase their chances of success.[4]

Therefore, substantial numbers of youth athletes continue to specialize and would benefit from individual guidance on how to effectively train through growth periods and adolescence to limit injury risk and continue to be successful. To our knowledge, a model that assists sports medicine practitioners to individualize training programs for specialized youth athletes based on the athlete's response to training load has not been fully developed. A theoretical framework was recently introduced by the authors to offer different load progressions based on a youth athlete's load tolerance but did not incorporate a number of other relevant factors.[46] In this article, we evaluate 4 key areas that underpin a novel athlete development model that could improve the effectiveness of training young specialized athletes: (1) sport specialization and athlete development, (2) biological maturation and utilization of percentage of predicted adult height, (3) motor deficits and neuromuscular training, and (4) recommendations for overall workload progressions (including competition:training load ratio).

A theoretical approach for assessing risk and determining workload progression through different developmental periods is also provided (see the Appendix, available in the online version of this article). Evaluating each of these 4 components may allow for appropriate risk stratification and recommendations on workload progressions and return-to-play strategies after injury.

## SPORT SPECIALIZATION AND ATHLETE DEVELOPMENT

A number of development pathways have been proposed regarding sport selection and training of young athletes for success. These include sport sampling, accumulation of a substantial number of hours of training through specialized sampling,[15] and early sport specialization. Sport sampling promotes participation in a variety of sports through preadolescent and adolescent stages of development to improve long-term athletic development.[15] Specialized sampling, which involves a greater emphasis on domain-specific sport-related activities, has been evaluated in youth soccer players where it was shown to lead to higher likelihood of elite-level success.[91] Early sport specialization and focus on a single sport prior to adolescence has been advocated by some stakeholders in the youth sports industry to theoretically enhance athletic success, but with little data to support this claim.[48,49]

There is conflicting evidence relating to early specialization and future sporting success. Nevertheless, there is a trend toward earlier specialization in many sports (eg, gymnastics, tennis, swimming, diving, and soccer).[88] Despite the popularity of specialization in a single sport at a young age, a recent systematic review demonstrated no superior benefit on task or career performance in populations of specialized athletes and multisport athletes.[48] These findings have led multiple some experts to suggest that diverse, multisport participation may result in enhanced skill acquisition and limit the potential risks of injury.[4,15,47,48]

A number of sports medicine organizations have recommended against sport specialization prior to middle or late adolescence. Most of these organizations cite injury, burnout, and potential for long-term health effects, although the data for long-term health consequences of sport specialization is relatively scarce. While the International Olympic Committee generally discourages early sport specialization, it also acknowledges that "appropriate diversity and variability of athletic exposure within a single sport, while supporting

Table 1. Degree of sports specialization and risk of all-cause injury[a]

| Degree of Specialization | Risk of Injury | Risk of Serious Overuse Injury | Risk of Acute Injury |
|---|---|---|---|
| Low specialization (0 or 1 of the following):<br>Year-round training (>8 months per year)<br>Chooses a single main sport<br>Quit all sports to focus on 1 sport or have only ever played 1 sport | Low | Low | Moderate |
| Moderately specialized (2 of the following):<br>Year-round training (>8 months per year)<br>Chooses a single main sport<br>Quit all sports to focus on 1 sport or have only ever played 1 sport | Moderate | Moderate | Low |
| Highly specialized (3/3 of the following):<br>Year-round training (>8 months per year)<br>Chooses a single main sport<br>Quit all sports to focus on 1 sport or have only ever played 1 sport | High | High | Low |

[a]Adapted with permission, from Myer et al.[78] Copyright 2015.

sufficient learning of foundational skills and sport-specific technique and biomechanics to minimize injury risk and optimize performance, can be acceptable and healthy."[6]

Many youth athletes are still choosing to specialize in a single sport. For these athletes, success may be achieved through specialized pathways with the proper guidance.[6] Unfortunately, there has been little guidance for athletes who specialize in a single sport at younger ages than recommended, leaving a large gap in evidence for minimizing injury risks and training young, specialized athletes.

## Overuse Injury Risk and Sport Specialization

Sport specialization has been defined on a continuum, and a degree of specialization can be used to stratify young athletes and subsequent injury risk with the following factors: (1) choosing 1 main sport, (2) quitting all other sports, and (3) training and competing >8 months in 1 year in 1 main sport.[47] Highly specialized athletes are those that choose 1 main sport, quit all other sports, and train/compete >8 months per year.[47] This high degree of specialization has been associated with greater overall injury risk, specifically overuse, and serious overuse injury risk but not acute injury risk (Table 1).[47]

Overuse injuries comprise >50% of injuries in young athletes,[16,20,47,92] and these injuries can also be classified by their level of risk. Serious overuse injuries have been defined as those where the athletes' physician recommended they stop sports for 1 month or longer (eg, bone stress injuries, and osteochondral injuries).[47] High-risk overuse injuries were defined by the American Medical Society of Sports Medicine as injuries that have a propensity to need surgery (eg, fifth proximal diaphyseal stress fracture, navicular bone stress injury, etc).[20] While it is critical to recognize and treat these injuries early (which likely involves complete cessation of sport), other lower risk injuries such as muscular injuries, apophysitis, and anterior knee pain syndromes may only require modification of workloads during rehabilitation, followed by staged progressions in training load.

Despite these injury risks, health-related quality of life of specialized young athletes may be high and equivalent to multisport athletes if they have mental resilience and a supportive parental environment.[16] In fact, even sport-related injury in young athletes has mixed effects on health-related quality of life indices with a recent study reporting only a mild decrease in mobility in young athletes with overuse injury, but otherwise no significant differences from the general pediatric population.[16] Despite theoretical risks, there is currently limited evidence to suggest that sport specialization results in more long-term negative health effects than multisport participation approaches.

When accompanied by movement diversity and variability of athletic exposure, participation in a single sport may result in positive health outcomes.[6] As such, in some instances, early specialization might be appropriate. It is likely that the influence of sport specialization on athlete development and injury risk is sport specific, and data are emerging on these risks.[8,26,45] There may be different times of optimal entry into sport based on the sport type.[78] Additionally, there are a number of factors that may influence the inherent risk of injury with sport specialization (Table 2). Consequently, certain individual athletes may carry more risk for overuse injury in the setting of sport specialization than others. Recommending that youth athletes avoid early specialization may be an oversimplification that ignores the importance of providing

Table 2. Sport specialization factors influencing risk for injury

| High Risk | Lower Risk |
| --- | --- |
| • High socioeconomic status | • Low socioeconomic status |
| • Geographic location: suburban | • Geographic location: rural |
| • Female gender | • Male gender |
| • Overuse injury | • Acute injury |
| • Earlier sport specialization (before adolescence) | • Later sport specialization (after adolescence) |
| • Individual, skill-specific sports (gymnastics, dance, tennis) | • Team sports (soccer, football, volleyball) |

specialized youth athletes with training and competition guidance and monitoring through vulnerable periods.

### What Environments Can Give Early Specialized Athletes the Best Chance of Success?

Although early specialization has been associated with negative outcomes, there are some general guidelines that can be followed to provide specialized youth with the best environment for physical and psychological development, reduced injury risk, and long-term sporting success. First, a well-rounded training program that includes strength, conditioning, and sport-specific skills should be a priority. Targeting physical qualities that are protective against injury (eg, muscular strength and aerobic fitness)[32] and associated with improved performance[94] represents an appropriate use of training time. Allocating training time to interventions that are known to decrease injury risk (eg, integrated neuromuscular training)[65] should be encouraged.

Second, in the off-season, highly specialized youth athletes with an athletic development pathway within a single sport should be encouraged to play a different sport. While this might seem contradictory to the premise of specialization, there are some advantages and these are unlikely to undermine investment in their main sport. Participation in a secondary sport provides a break from the repetitive movements of their primary sport (eg, repetitive throwing, hitting, or jumping activities), may result in the development of more adaptable movement patterns,[18,79] has been associated with superior perceptual expertise (decision making and ability to "read the play"),[7] and may help protect against some factors associated with burnout.[35]

## BIOLOGICAL MATURATION

The adolescent growth spurt is recognized as a stage of development when athletes are more susceptible to certain types of injury, specifically those injuries associated with the growth plate and overuse.[64] Onset of the growth spurt typically occurs at 9 to 10 years of age in girls and at 11 to 12 years in boys, yet this can vary substantially across children with some individuals experiencing the growth spurt well in advance or delay of their peers.[56] During this phase of development, youth experience rapid gains in stature and then mass, typically peaking between 9 and 10 cm per annum in boys and girls.[100] An equivalent growth spurt in mass occurs 6 to 9 months later, with girls and boys experiencing peak gains of approximately 8 to 10 kg per year.[100] Pubertal gains in mass occur predominantly as a result of increases in fat and fat-free mass (ie, muscle, skeleton, soft tissues, organs); however, there is variance between the sexes.[58] Whereas girls experience greater gains in absolute and relative fat mass during puberty, boys experience greater gains in absolute and relative lean mass.[58] Percentage of predicted adult height (PPAH), using methods advanced by Malina et al[57] (requires assessment of child's age, height, mass, and midheight of biological parents) and growth rates (height and mass) can be used to estimate when athletes are entering and exiting the adolescent growth spurt (Figure 1). For example, PPAH values can be used to estimate age at take-off (85%), the interval of peak height velocity (PHV) (~91%), or the end of the deceleration phase of the adolescent growth spurt (~96%).[89] A percentage band (~85%-96% of PPAH) was shown to correctly identify 91% of players as being within or outside the adolescent growth spurt in a longitudinal study of academy soccer players.[82]

The prevalence of overuse injuries across youth sports programs ranges from between 37% and 68%.[20] Overuse injuries are especially common during the adolescent growth spurt and include Sinding-Larsen-Johansson syndrome, chondromalacia, Osgood-Schlatter and Sever disease, osteochondritis dissecans, and lower body stress fractures. The majority of these injuries relate to the physeal plate, and their occurrence follows a pattern of distal-to-proximal growth.[20,68] Retrospective analysis of maturation and injury incidence in academy footballers reveals that cases of Sever disease (ie, heel) cluster around the start of the growth spurt (85% PPAH), whereas the peak incidence of Osgood-Schlatter disease (knee) approximates the peak of the adolescent growth spurt (89% PPAH).[68] In contrast, cases of spondylosis (lower back) tend to cluster around the deceleration point of the adolescent growth spurt (96% PPAH).

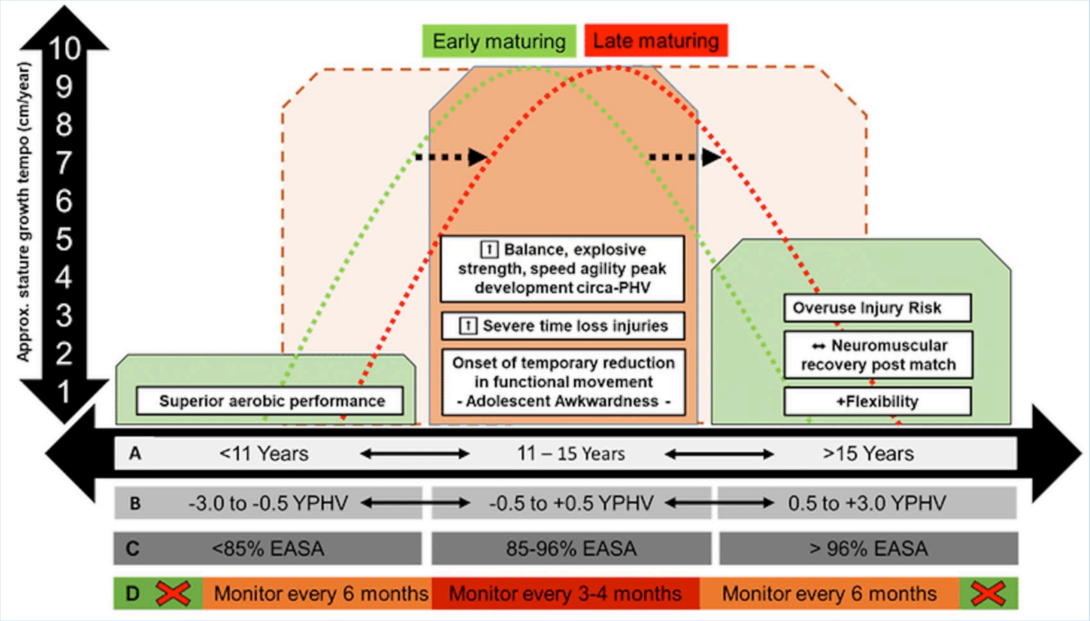


Figure 1. Use of PPAH (EASA) to determine location in adolescent growth curve. EASA, estimate adult stature attained; PPAH, percentage of predicted adult height; YPHV, years from peak height velocity.

Reproduced with permission from Towlson C, Salter J, Ade JD, et al. Maturity-associated considerations for training load, injury risk, and physical performance in youth soccer: one size does not fit all. *J Sport Health Sci.* 2021;10(4):403-412. doi:10.1016/j.jshs.2020.09.003. Copyright 2021.[102]

## Bio-Banding

A number of strategies can be employed to reduce the risk of overuse and acute injuries during the adolescent growth spurt, including the routine measurement of growth and maturation, the prediction and identification of the adolescent growth spurt, the monitoring of injury symptomology, and the prescription of developmentally appropriate training programs (load and content). Jan Willem Teunissen, a former movement scientist at Ajax Football Club (AFC), widely recognized as one of the world's leading soccer academies, described a bio-banded (ie, maturity matching) training intervention[108] that was employed to help academy players transition more effectively through the adolescent growth spurt and reduce injury risk. Players entering the growth spurt were assigned to a "conditioning program" that involved reductions in training load and activities that involved significant amounts of acceleration and deceleration. These changes were coupled with an increased emphasis on activities that developed and/or maintained coordination, balance, core strength, and mobility and involved the retraining of fundamental and sport-specific skills.[108] Applying an equivalent bio-banding strategy across a competitive season, sports scientists at AFC Bournemouth reported marked reductions in both injury incidence and burden among players who were within the adolescent growth spurt (Cumming SP. Advances in the study and consideration of growth and maturation in youth football. Paper presented at: Manchester United Football Club Sports Science and Medicine Conference; November 13, 2020; Manchester, UK). Although the results of these studies are encouraging, further research is required to validate these findings, to better understand how changes in training load and content may mitigate injury risk through the adolescent growth spurt. It is equally important to consider the impact of pubertal timing, as youth who experience growth spurts at an older age may be at greater risk because of increased training load and competition demands. The period of growth prior to and during the PHV is when an athlete may be most vulnerable to injury and when it is most important to modify training and competition loads.

## MOTOR AND COORDINATION DEFICITS

Sport specialization has typically been associated with overuse injury, while neuromuscular deficits are primarily thought to be a major contributor to acute injury such as anterior cruciate ligament (ACL) tears. Coordination deficits have recently been identified in specialized, young female athletes.[19] This could potentially draw a theoretical association with sport specialization and acute injuries such as ACL tears. Risks of acute knee injuries such as ACL tears are reduced with proper neuromuscular training[83] and to an even greater extent when applied in younger athletes.[81] Neuromuscular training, targeting coordination deficits that increase injury risk, may ultimately prove useful for reducing the incidence of both acute and overuse injuries in young athletes.[40,41,70-77,80,81,93,95-99]

A recent study examined relative hip and knee joint angular motion variability among adolescent female sport-specialized and multisport athletes to determine how sport specialization may affect motor coordination acquisition in young athletes.[19] Via questionnaire data analyses, sport-specialized athletes were defined as having ≥2 years of participation in 1 sport and fewer than 2 years participation in any other sports. The sport-specialized group exhibited increased variability in hip flexion/knee flexion coordination, knee flexion/knee abduction, and knee flexion/knee internal rotation while landing during a drop vertical jump task.[18] The authors concluded that these altered coordination strategies involving the hip and knee joints, which may underpin unstable landings, inefficient force absorption strategies, and/or greater contact forces, can place the lower extremities at higher risk of injury in athletes who specialized earlier in their young careers.[18]

In the largest investigation to date, 782 soccer, basketball, and volleyball players were classified as prematurational at the initial visit, were followed longitudinally, and then were reassessed at a second visit in which they were classified as postmaturational.[10] In this longitudinal cohort, sport-specialized athletes exhibited a smaller increase in peak knee extensor moment (desirable sagittal plane power) and a larger increase in peak knee abduction moment (injury risk–related frontal plane load) across visits compared with the multisport group.[19] Thus, sport specialization before pubertal maturation may promote worsened biomechanics that can propagate through maturational development in young athletes.

Children who specialize early (eg, prior to maturation) in a single sport may execute less diverse movement capacity even within a given sports skill execution. This theory of shunted diversity in movement skills was evaluated in a soccer-specific virtual reality header assessment to characterize the movement of young athletes who were grouped by their degree of sport specialization (Riehm C, Bonnette S, Riley M, et al. Movement complexity differentiates specialized and non-specialized athletes in a virtual reality soccer header task. Paper presented at: The 14th Annual Emory Sports Medicine Symposium; May 1-2, 2021; Atlanta, GA). During the virtual reality header task, the early specialized and nonspecialized athletes demonstrated differences in gross body movement complexity during the soccer-specific header task. Specifically, the nonspecialized athletes exhibited more complex movement profiles during the soccer header than the specialized athletes (Riehm et al, The 14th Annual Emory Sports Medicine Symposium). Although not empirically tested in their study, the authors postulated that the more complex movements of the nonspecialized athletes, over time, would lead to a lower likelihood of overuse injury due to less homogenized muscle activation patterns, while the constrained movements in specialized athletes may increase chronic joint load and increase risk of overuse injury (Riehm et al, The 14th Annual Emory Sports Medicine Symposium).

Without opportunities to naturally experience a variety of load adaptive stimulus from sport diversification during maturation, youth athletes may not fully develop neuromuscular patterns that may be protective against injury and potentially develop movement strategies that increase injury risk.[17,19,25,36,40,72,86] Alternative solutions to sports specialization, including planned diverse motor skill opportunities and strength development during the growing years, combined with planned integrative neuromuscular training, may help optimize the potential for success in young athletes.[6,24]

## OVERALL WORKLOAD AND TRAINING LOAD PROGRESSIONS

### Competition to Athletic Development Training Ratio

Talented youth athletes have opportunities to train and compete for a number of different teams or representative levels within their primary sport and some late specializing athletes participate in more than 1 sport. This presents challenges that are unique to youth athletes. For example, managing individual player load and recovery to optimize performance and health of youth athletes requires a coordinated approach across various teams, representative levels, and sports not typically required for elite adult athletes.[10,90] These challenges, along with the tendency for stakeholders in youth sport to prioritize short-term performance achievements over long-term athlete development,[20,69] mean that some talented youth athletes are at risk of experiencing high training and competition loading, insufficient recovery, and a high competition-to-training ratio. This might be especially true for specialized youth, for whom a main goal of participation may be to reach elite-level status.

Substantial research has explored the relationship between training load and negative health outcomes, including injury.[21] The role of competition-to-training ratios within overall load has received comparatively little attention. One of the earliest models of long-term athlete development recommended that youth progress from a competition-to-training ratio of 25:75 during early adolescence to a 50:50 ratio in late adolescence.[2] Importantly, competition-specific training was intended to be included in the proportion of time spent in competition. For example, minutes of time spent in game-based training drills should be included as competition minutes. The value of these recommended competition-to-training ratios have not been empirically tested, and optimal ratios are likely to vary by sport. Other widely implemented youth athlete development frameworks[14,34] and consensus statements[6] do not make specific recommendations for competition-to-training ratios but generally advocate that youth athletes aspiring to transition to elite representation progress training in order to develop the competencies required to perform in higher levels of competition. Consequently, exposure to a higher competition load or competition at higher levels without first accomplishing the goals of focused, intensified training is discouraged (Cumming SP. Advances in the study and consideration of growth and maturation in youth football).[14,34]

A number of studies have explored the training and competition practices of youth athletes, but very few of these have distinguished the separate contributions to load of training and competition. Studies also typically report group average training and competition loads making it difficult to determine the competition-to-training ratios of individual athletes. Information on individual athletes would be particularly useful because it is the most talented individuals who are more likely to represent different teams, participate in different competitions, and even play different sports.[1] This pattern of participation is likely to disproportionately increase competition exposure. In a small number of studies that have reported training and competition loads, and also highlighted individual athlete loads, there are some examples of youth experiencing very high competition loads.[37,38,84] In studies of youth rugby players, Hartwig et al[37,38] and Phibbs et al[84] showed that in some weeks during a season some individual athletes played between 3 and 6 competitive matches. Competition-to-training ratios were not reported in these studies.

The impact of high competition-to-training ratios on youth athlete health and performance is not known, but negative outcomes are possible.[13,37,59] Across a wide range of sports, youth competition injury incidence is consistently higher than injuries sustained during training.[13,59] Competition, but not training workloads, increases injury risk in youth team sport athletes.[37] A recent study showed a 32% higher match volume in youth rugby players who sustained an injury than those who did not, whereas there were no differences in training volumes between injured and noninjured players.[37] Also, in this study each 1-hour increase in weekly match volume increased injury risk by 41% (odds ratio = 1.41; 95% CI = 1.14-1.74; $P = 0.001$). One interpretation of these findings is that spending a high proportion of time in competition results in athletes' spending insufficient time preparing physical capacities during training. These physical capacities are likely to be protective against injury and to ensure athletes are prepared for the demands of competition.[31]

Compared with training, competition also increases exposure to injury risks that are nonmodifiable. For example, in many team sports, collision events contribute disproportionately to injuries.[27] As these inciting events are usually unavoidable, the risk of collision injuries increases with increasing exposure to competition. Interestingly, the risk of collision injuries and also overuse injuries may actually increase during adolescence as a result of a developmental shift toward greater risk-taking behavior.[9,22] For example, in a study of talented youth tennis players, higher risk-taking behavior was related to a higher number of time-loss overuse injuries and to higher overuse severity.[104] A culture of risk taking during sports competitions along with an increased tendency for the developing youth athlete to take risks provides further evidence for the need for practitioners to carefully monitor competition-to-training ratios.

Practitioners can easily calculate competition-to-training ratios by determining the number of minutes spent in these activities each week. While there are no clear guidelines for prescribing optimal ratios, practitioners in specific sports will likely be able to determine when competition is being disproportionately prioritized over training.

## Adolescents Are Not Mini Adults!

In an attempt to understand the positive and negative effects of training, we recently systematically reviewed the relationship between workloads and physical performance, injury, and illness in adolescent athletes.[33] Of the 23 articles that met the selection criteria, only 4 were associated with negative outcomes. Of these,

- greater training duration and poorer stress/recovery scores were associated with greater illness[12]
- rapid increases in training load were associated with increases in injury rates[30]
- greater increases in training load led to more groin pain[53]
- 1.0% to 3.8% of athletes (1) were both highly stressed and poorly recovered; (2) had high training volumes and were poorly recovered; or (3) had high training volumes, were highly stressed, and poorly recovered.[39]

These findings suggest that (1) negative responses to training do happen, but not often (at least not commonly researched and reported) and (2) clearly there is a point where training (and other physical activity) shifts from providing benefits to becoming a problem.

When training youth athletes, 1 factor (among many) that warrants consideration is age. When prescribing training load, practitioners often refer to *age-appropriate training*. We can think of age in 3 ways: (1) chronological age, (2) biological age, and (3) training age. Age is a moderator of the training load–injury relationship. In other words, depending on their *chronological age*, athletes have a better (or worse) ability to tolerate training load. However, the moderating effect of age is not limited to chronological age. *Training age* (analogous to training history) and *biological age* can also affect an athlete's ability to tolerate training load. PHV (where maximum rate of growth occurs) is commonly associated with increased injury risk.[87,105]

A recent study investigated anthropometric measures and growth as risk factors for overuse injuries in youth (aged 10-15 years) soccer players.[87] An increase in leg length over the season was associated with an increased risk of overuse injuries. In another study, van der Sluis et al[105] examined the relationship between adolescent growth spurts and overuse injury. Later maturing players had a higher incidence of overuse injury than their earlier maturing counterparts both in the year before PHV and the year of PHV. Players were especially susceptible to injury between 13.5 and 14.5 years of age. Common recommendations for training adolescent athletes include (1) monitoring age-specific anthropometric and growth-related risk factors and (2) minimizing abrupt changes in training load during these growth spurts.

## Increasing Capacity Involves More Than Simply Progressing Training Load

Although progressive and gradual increases in training load are known to improve load-capacity,[31] health factors can also influence performance and injury outcomes.[106] For example,

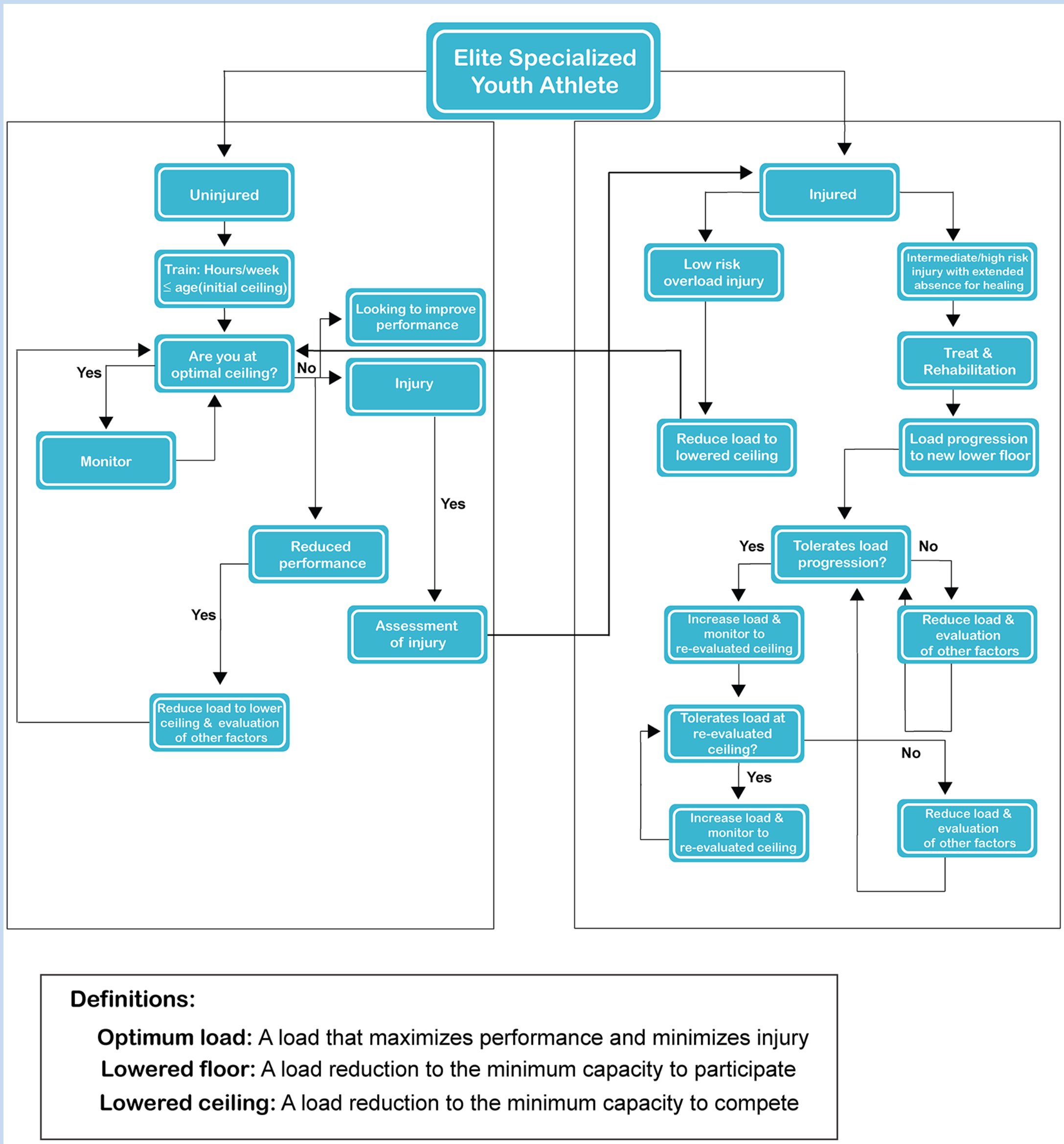


Figure 2. Workload progression flowchart for uninjured and injured elite specialized youth athletes.

academic and emotional stress,[44] anxiety,[51] and stress-related personality traits[54,101] all increase injury risk. Furthermore, 1 study showed that adolescent athletes who slept fewer than 8 hours per night were 1.7 times more likely to sustain an injury than those who slept 8 or more hours per night.[67] In a study of 496 adolescent athletes from 16 different sports, sudden increases in training volume and intensity combined with a reduction in sleep volume were associated with a 2.3-fold higher injury risk.[107] Given that adolescents can be particularly vulnerable to poor sleeping habits, academic stress, and psychological stress, these factors should be considered when planning and prescribing training programs for these individuals.

The training dose-response is of importance to coaches and practitioners in order to determine the optimum training load to maximize positive outcomes (ie, fitness, performance), while minimizing negative outcomes (ie, fatigue, burnout, injury). Decisions on training load progressions may be based on whether the athlete is injury-free, at low risk of injury, or at higher risk of injury. Athletes need to progress from their current capacity (ie, their "floor") to the capacity required of the sport (ie, their "ceiling").[28] The rates of progression may vary based on risk stratification, particularly the presence or lack of injury. Athletes with lower risk injuries may continue to load and progress, but with a modified ceiling, while athletes with higher risk injuries need to be evaluated and return to play with a slow rate of workload progression (Figure 2).

Although higher chronic training loads have been associated with better performance[43] and lower injury risk[42,43] in adults,

| Low Risk Athlete: "Load Tolerant" | Train + Compete |
|---|---|
| **Risk assessment per associated question sets:**<br>☐ Low degree of sports specialization<br>☐ No injury<br>☐ Workload hrs/week < age<br>☐ Sports training ratio <2:1<br>☐ Competition:training ratio <1:3<br>☐ ACWR >0.8 and <1.3<br>☐ > 96% PPAH<br>☐ Motor and coordination: Low risk | **Action steps:**<br>☐ Continue training and competing toward optimum workload<br>Increase workload by < 20% per week to ceiling<br>➢ Serial monitoring every 4-6 months |
| **Moderate Risk Athlete: "Load Naïve"** | **Train + Compete with Caution** |
| **Risk assessment per associated question sets:**<br>☐ Moderate degree of sports specialization:<br>☐ Suspected or low-risk overuse injury<br>☐ Workload hrs/week < age<br>☐ Sports training ratio >2:1<br>☐ Competition:training ratio <1:1<br>☐ ACWR >1.5<br>☐ < 85% PPAH<br>☐ Motor and coordination: Moderate risk | **Action steps:**<br>☐ Increase frequency of serial monitoring<br>☐ Moderate decrease in workload<br>☐ Temporarily reduce ceiling<br>☐ Return to sport with reduced/moderate rate of load progression<br>☐ Call your sports medicine provider if persistent pain for 2 weeks or 1 week in high-risk area (low back, shoulder, elbow)<br>➢ Serial monitoring: weekly to monthly |
| **High Risk Athlete: "Load Sensitive"** | **STOP & ADAPT** |
| **Risk assessment per associated question sets:**<br>☐ High degree of sports specialization<br>☐ Suspected or high-risk overuse injury<br>☐ Workload hrs/week > age<br>☐ Sports training ratio >2:1<br>☐ Competition:training ratio >1:1<br>☐ ACWR > 2.0<br>☐ 85-96% PPAH<br>☐ Motor and coordination: High risk | **Call your sports medicine provider and do the following:**<br>**Action steps:**<br>☐ Significant decrease in workload<br>☐ Reduce ceiling<br>☐ Rehabilitate and treat<br>☐ Return to sport with slow increase in workload by < 10% per week to ceiling<br>➢ Serial monitoring: daily to weekly |

Figure 3. Youth Athlete Action Plan: risk stratification and return to sport for the specialized adolescent athlete. ACWR, acute:chronic workload ratio; PPAH, percentage of predicted adult height.

both low and high training loads are associated with greater risk of injury[50] and poor well-being[66] in adolescent athletes. Performance changes in response to a conditioning program in adolescent (mean age = 16.9 years) and adult (mean age = 25.5 years) athletes have been investigated.[29] Despite having lower training loads, adolescent athletes exhibited greater improvements in maximal aerobic power and muscular power. Collectively, these results demonstrate that adolescent and adult athletes adapt differently to a given training stimulus and that training programs should be modified to accommodate differences in training age. Importantly, adolescent athletes do not need excessive training loads to elicit positive training adaptations. These findings, taken with those of others,[107] suggest that prescribing moderate training loads with small fluctuations is best practice for most adolescent athletes.

## Developing Load-Capacity in Specialized Adolescent Athletes

Several factors (eg, age, injury history, training history, lower-body strength, and aerobic fitness) moderate the workload-injury relationship, resulting in some athletes having greater load tolerance than others.[60-62] Consequently, these historical factors, along with information on sport specialization risk, PHV, and motor and coordination deficits can be used to prescribe and manage training loads in load-tolerant (low risk), load-naive (moderate risk), and load-sensitive (high risk) adolescent athletes. Load-sensitive athletes with multiple risk factors may need medical evaluation, frequent monitoring, and a program designed to restore local tissue and sport-specific capacity. Load-naive athletes, or those with moderate risk factors, will likely benefit from serial monitoring and should train and compete with caution, while load-tolerant athletes may only need occasional monitoring and progress to optimum loads. A guide to training prescription for adolescent athletes with different risk factors is shown in Figure 3.

## CONCLUSION

Although early specialization may pose a risk to some athletes, it is possible to have positive experiences and success with specialized training. When prescribing training load, practitioners should consider moderators of the workload-injury relationship (eg, age, training history, strength, aerobic fitness) and injury risk factors (eg, injury history, poor biomechanics, and biological maturity) that can affect load tolerance. Given the increased risk associated with high competition loads in youth athletes, training programs designed to develop physical qualities and neuromuscular control may offer a protective effect against injury while also enhancing performance. When considering the overall workloads of elite specialized athletes, coaches, and sports medicine practitioners should look for opportunities to develop physical qualities, flexible and adaptable movement strategies, and sport-specific skills, within a framework that prioritizes preparation (ie, training) over competition.

## PRACTICAL RECOMMENDATIONS

- Serial monitoring of workloads, growth, and maturity and minimizing of high competition-to-training ratios is recommended to decrease injury risk. (SORT B)
- While sport specialization carries risks of overuse injury, it may be possible to successfully train a single-sport young athlete and intensify training in load-tolerant athletes when approaching skeletal maturity. (SORT C)
- Restrict total workload (training and competition) to fewer hours per week than a child's age with increases and reductions based on load tolerance. (SORT B)
- Coaches (and parents) of youth athletes should exercise caution when managing workloads, particularly when approaching and during PHV to limit growth-related overuse injury. (SORT B)
- Young female specialized athletes may develop motor and coordination deficits compared with multisport athletes. These coordination deficits may be corrected with integrated neuromuscular training programs. (SORT B)
- More rapid progressions in workload can be prescribed in skeletally mature, load-tolerant young athletes, while changes in workload should be smaller for load-naive (skeletally mature) or load-sensitive young athletes. (SORT B)

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