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Youth sport: Friend or Foe?

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Abstract

Participation in youth sport has been promoted as part of a healthy lifestyle, with benefits for physical fitness, social development, and mental wellbeing. Yet, sport carries an inherent risk of injury, which for young athletes may have both immediate and long-term consequences. Amidst significant public debate about the pros and cons of youth sport, this review considers the physiological, psychological, and social factors that inform decisions around youth sport participation. With particular emphasis on growth and maturation, early sport specialization, and injury prevention, it highlights the unique features of the youth sport environment that can influence lifelong musculoskeletal health and physical activity behaviour. Though there have been few robust, longitudinal studies, current evidence suggests that sport has positive effects on child and adolescent wellbeing when maturity status and training load are managed appropriately.

Key Words: Youth, Sport, Injury, Maturation

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1. Introduction

Childhood and adolescence represents a period of life when sport participation is at its highest. Indeed, it is estimated that 27 million youth between the ages of 6-18 years participate in team sport, and 60 million participate in some form of organised sport, in the United States alone [1]. Of these, roughly 44 million are multi-sport athletes [1]. Although this is typically viewed as a positive element in the fight against sedentarism and an opportunity for youth to gain beneficial skills and life experience, sport holds implications for health-related outcomes that are becoming more widely understood. This has led to a growing public discourse about the relative merits and risks of youth sport, and what it means for the long-term health and wellbeing of those who participate.

There has been increasing recognition that the youth sport context is fundamentally different than that experienced by intercollegiate or adult populations, which have dominated the sport medicine literature. Youth athletes (i.e., those aged 10-18 years) undergo intense periods of physiological, biomechanical, and psychosocial growth in a climate of highly variable demands imposed by academic, social, employment, and sport commitments. Consequently, physical and psychological stresses interact in unique ways. Youth athletes are also in a vulnerable situation where multiple stakeholders are involved and may have competing interests, which ultimately influence their decision making or decisions made on their behalf. Moreover, the vast majority of youth sport is played in community settings where resources and expertise can be limited, therefore impacting access to coaching and medical services which may be of variable quality. Altogether, these factors necessitate a careful balance between the benefit of sport participation with the risks of injury, burnout, and diminishing athletic achievement. Therefore, it is imperative to understand the current state of the evidence in order to provide best practice care and navigate the complex ethical milieu that defines the youth sport environment.

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2. The paradox of sport participation

The risks of a sedentary lifestyle have been well established, including elevated likelihood of overweight/obesity and associated non-communicable diseases, reduced mental and social wellbeing, and all-cause morbidity and mortality [2]. These effects can begin to manifest in childhood and adolescence, particularly for those who do not accumulate recommended amounts of moderate-to-vigorous activity on a daily basis [3]. Recognizing the obesity pandemic and the potential years lived with disability following early onset of lifestyle-related ill health, efforts have been made to encourage and maintain youth engagement in a variety of physical activities, including sport.

Sport participation is associated with numerous benefits during childhood and adolescence. These include improved aerobic capacity, muscular fitness, and bone health [4]. Moreover, sport contributes to enhanced motor competence [5], can alleviate symptoms of depression, anxiety, and stress, and facilitate increases in quality of life, subjective wellbeing and vitality [6]. Physically active children report higher self-perceptions and cognitive functioning relative to those who are inactive [7], and sport offers opportunities to learn better emotion-regulation, fine-tune inter-personal skills and develop quality peer relationships [5]. Importantly, there is evidence that sport participation is positively associated with both academic engagement and achievement [8].

Despite its known benefits, sport participation declines with age through adolescence, particularly for girls [9]. This may be attributed to a number of factors including competing demands between academic and social commitments, limited access to affordable opportunities, the development of alternative interests, issues around self-presentation arising alongside puberty onset, and conformity to traditional gender roles [9]. Injury and fear of injury are also salient concerns that prompt drop out from sport, or increasingly prevent initial enrolment. As many as 70% of children drop out of organised sport before age 13 [10] and injury is a major contributing cause. To illustrate, 20% of elite athletes in a sample of 1,387 Canadian high school students (mean age 15 years) reported injury as their reason for leaving sport [11]. This has implications for immediate and

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maintained physical activity across the lifespan, and speaks to both the actual and perceived impact of injury in this setting. Indeed, herein lies the crux of the current youth sport safety debate.

As we endeavour to increase sport participation as a means of physical activity, we must acknowledge that sport carries an inherent risk of injury. Population-level incidence is challenging to determine due to limited means of establishing exposure across organized and unorganized sport settings; however, based on hospital data, sport is a leading cause of injury amongst young people. In the US, it has been estimated that ~59 of every 1000 individuals aged five to 24 will sustain a sport or recreation-related injury each year, accounting for 64% of the sport and recreation injury burden in the American population [12]. Based on surveillance through the European Injury Database (IDB), it is estimated that 1.3 million children under the age of 15 are treated in hospital for sport injuries each year [13]. In the EU, team ball sports account for nearly 40% of all hospital-treated sport injuries, largely owing to their relative popularity and the likelihood of player-to-player collision. Soccer and basketball are the greatest contributors to this burden, particularly amongst boys [13].

In the short-term, these injuries can have significant consequences. Many will require medical attention, which can include surgical repair and lengthy rehabilitation, and can result in time lost from school and other activities. Athletes who are unable to participate in their sport for a period of time often report feelings of social isolation, fear of re-injury, loss of motivation, and depending on the length of recovery may experience measurable setbacks in fitness and technical development [14]. Injuries may also require parents to be absent from work whilst attending appointments. Youth sport injury therefore represents a meaningful financial burden on families and the health care system in general. Conservative estimates place the overall cost of sport injury in the EU at around 2.4 billion Euro annually but, notably, proportional estimates are not available for youth compared to adult sport [13].

In the longer term, musculoskeletal (MSK) injury has been associated with significantly increased risks of osteoarthritis and other chronic conditions [15]. Although concussion and its

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long-term sequelae are currently of primary concern in the youth sport context, awareness of the potential consequences of sport injury in general is becoming more ubiquitous amongst relevant stakeholders. Therefore, balancing the risks and benefits of youth sport participation is likely to gain greater emphasis in decision making and policy discussions, with trickle-down effects in terms of informed participation, coach training, and medical provision.

3. The role of growth and development

The processes of growth and maturation play central roles in young athlete development and have important implications for competition, talent identification, and the prevention and treatment of injury. Although terms such growth, maturation and development are often considered synonymous, it is important to recognise these processes as independent, yet related. Whereas growth pertains to changes in body size, shape, and/or composition; maturation refers to the act of progression from conception towards the adult/mature state. Maturation occurs, and can be measured, in multiple biological systems (i.e., hormonal, skeletal, somatic, sexual, dental) and can be defined in terms of status, tempo and timing [16]. Status refers to the stage of maturation that an individual is experiencing at the time of observation (e.g., pre-pubertal, pubertal, post-pubertal); whereas timing refers to the age at which specific maturational events, such as menarche or peak-height-velocity, occur. Tempo refers to rate at which the maturation process progresses. Children of the same age can vary significantly in their rates of maturation with some individuals maturing well in advance or delay of their peers [17].

Development entails the biological, psychological, cognitive, emotional, social and motor changes in function that occur from birth to adulthood. With age, children develop a greater capacity to engage in abstract learning, to process and retain information, and to rely on sophisticated reasoning skills [18]. As a consequence, they become more able to partake in and enjoy complex and time-intensive activities, solve more challenging problems, rationalise their successes and failures, and make informed decisions relative to risk. As children age they also develop greater capacity to experience, express and manage their own emotions, while also

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appreciating the emotions and perspectives of others [19]. Thus, they become more capable of establishing positive and rewarding relationships with both peers and adults, following instruction, and considering the belief and perspectives of others. From a perceptual-motor perspective, children develop greater capacity to acquire, organise, and interpret sensory information, resulting in the development of more sophisticated and synchronised movement patterns [28]. These developments are particularly salient in a sporting context where older and more experienced athletes become more capable of executing complex motor skills.

Puberty is the process through which a child's body matures into the adult state and is of particular relevance to those involved in the identification, development and management of young athletes. Puberty is a biologically driven process that occurs between approximately nine and 16 years of age and entails dramatic changes in size, shape, function, and appearance. The timing of puberty is determined by a combination of genetic and, to a lesser extent, environmental factors and can vary between individuals by up to six years [21]. As such, the age at which children enter puberty can vary substantially. Girls also generally enter puberty two years in advance of boys, though there is more variation within the sexes than between [16]. The timing of puberty has also been shown to vary relative to ethnicity, with certain groups tending to mature in advance or delay of others, though again variance within ethnic groups is greater than variance between [22].

The pubertal growth spurt is the most salient feature of puberty and typically starts at nine years for girls and 11 years for boys. The peak of the growth spurt tends to occur between 11 and 12 years for girls, and 13 to 14 years in boys [23]. During this phase, children experience marked gains in stature (peaking at between three to four inches per year) before encountering a similar spurt in body mass six to nine months later. Pubertal gains in mass are largely attributable to changes in fat free mass (i.e., skeleton, muscles, soft-tissues, organs); however, there is notable variance across the sexes. Whereas boys generally experience proportionally greater gains in fat-free mass, girls experience comparatively greater gains in fat mass [24]. Coupled with sex-specific changes in

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physique, fat distribution, and the development of secondary sex characteristics, these changes contribute to widening gaps in athletic prowess and sport participation between the sexes.

The timing at which children enter puberty has important implications for athlete selection and performance, and may also influence injury risk. Children who mature in advance of their same-age peers are the first to experience the physical and functional changes associated with puberty. In sports that demand greater size, strength, and power, this affords an athletic advantage, especially when competing within age-restricted divisions [16,25]. Boys who mature in advance of their peers are taller and heavier and tend to experience greater gains in fat free mass. Consequently, they generally outperform their later-maturing peers from the onset of puberty, continuing through to late adolescence [26]. Evidence suggests, however, that these advantages are attenuated and/or reversed in adulthood. Girls who mature in advance of their peers are also taller and heavier, though a greater proportion of these gains can be attributed to fat mass. Whereas early maturing girls may possess an advantage in sports that demand greater size or absolute strength (e.g., tennis) they tend to be disadvantaged in activities that require endurance, agility, or aesthetic qualities (i.e., cross country running, gymnastics, dance) [27]. Boys and girls are who enter puberty at a much older age (i.e., three to four years after their early maturing peers) are considered late maturing. With late maturing children, the growth spurt may coincide with important points in their athletic careers when workloads are significantly increasing and selection to elite pathways may occur [17]. Growth-related decrements in functionality and performance may serve as a handicap for these athletes, temporarily masking their true ability or potential.

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The physical and functional consequences associated with variance in maturation timing are reflected in the proportions of early and late maturing children in specific sports. Prior to the onset of puberty, early, on-time and late maturing boys and girls tend to be proportionally represented in youth sports programmes. From the onset of puberty, however, maturation selection biases can be observed. In sports such as soccer, football, rugby and tennis, there is a selection bias towards early maturing boys and against late developers [28]. This bias tends to increase with age and is most evident in elite level programs. A recent study of player selection across two football academies demonstrated that between 60-80% of all boys in the under-16 and under-17 age groups were early maturing [29]. In contrast, late maturing boys constituted only 3-4% of the total academy population in these age groups. Similarly, from the age of nine years, tennis increasingly selects for girls who mature early and are, as a consequence, taller and stronger [30]. In contrast, girls who are late maturing are over-represented in activities such as ballet [31]. While much of this selection bias reflects underlying changes in biology, it should be noted that the physical and functional changes associated with puberty may also indirectly impact athlete selection though self-perceptions and the evaluations and reaction of significant others (i.e., peers, parents, coaches, educators) [32].

4. Maturation and musculoskeletal injury

Both the timing of puberty and its associated selection biases may have implications for injury risk. Rapid changes in size and function provide an athletic advantage, but can also make athletes more susceptible to MSK injury. This is especially true when coupled with increasing demands of both training and competition that come with increasing age and/or skill level. In a detailed review, DiFiori and colleagues report that overuse injury prevalence ranges from 37% to 68% across various youth sports [1]. These injuries are more likely to occur during adolescent growth spurts, where physes, apophyses, and articular surfaces are less resistant to tensile, shear, and compressive forces than pre-pubescent or mature bone due to a lack of collagen and calcified tissue [1]. Overall, physeal injuries have been reported to account for 15-30% of emergency department MSK injuries in children and ~40% of acute cases are sport-related [33].

Physeal plate injuries are a unique consideration for those working with paediatric patients. Asynchronous growth between skeletal and ligamentous structures leads to ligament stresses that transfer through the proportionally weaker physeal plate, causing shearing or compression-type separation through the physeal layers [34]. There is also an age-adjusted decrease in bone mineral density that precedes peak height velocity, which may pose an increased risk of Salter-Harris fracture [35]. From 1-30% of youth MSK emergency department visits are reported to be for

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physeal fractures, but inconsistencies in injury reporting and lack of exposure data limit more robust estimates [36].

Physeal injuries resulting from overuse are also common amongst paediatric athletes. Chondromalacia describes softening of the articular cartilage, and is the most common type of anterior knee pain in paediatric populations [34]. Other hallmark injuries seen during periods of skeletal growth are traction apophyseal injuries such as Sinding-Larsen-Johansson syndrome, Osgood-Schlatter disease and Sever's disease. Sinding-Larsen-Johansson syndrome is characterized by traction apophysitis of the inferior patellar pole. Osgood-Schlatters syndrome, which is the most common apophyseal injury (estimated prevalence of 20% in boys and 13% in girls [37]), presents as patellar tendinopathy at the ossification centre on the tibial tubercle. Sever's disease is a result of repetitive Achilles tendon stress at the site of insertion on the apophysis of the calcaneus [37]. Care for all of these conditions includes pain palliation and strengthening exercises, but is driven primarily by load management. Such injuries usually resolve with rest, but some may result in growth disturbance and joint deformity if not properly diagnosed and treated [1].

Higher-risk overuse injuries seen during adolescence include osteochondritis dissecans and lower limb stress fractures. Kessler and colleagues investigated the incidence of osteochondritis dissecans of the knee in a retrospective cohort of over one million patients aged two to 19 years [38]. They found that risk trebled for those aged 12-19 compared to those aged 6-11 years [odds ratio (OR) = 3.3; 95% CI: 2.71 – 5.41], which was hypothesised to be related to sport participation and increased loading of the joint [38]. Stress fractures are similarly related to repetitive forces through an immature skeletal system that, with demanding training schedules, has not had adequate time to recover and remodel. Such injuries carry a good prognosis if identified and managed appropriately, but if left untreated may lead to significant chronic pathology that threaten future sport participation and result in long-term disability [1].

Although overuse injuries are the primary concern associated with MSK development, puberty also initiates sex-specific increases in acute injury risk. For example, anterior cruciate

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ligament (ACL) injuries occur, on average, 3.5 times more frequently in female athletes, a discrepancy that does not emerge until the onset of puberty [39]. This has largely been attributed to hormonal and structural differences (i.e., Q angle and knee ligament laxity), but mechanism of injury is generally related to neuromuscular recruitment patterns and landing techniques arising from suboptimal movement tendencies [39]. Therefore, early maturing girls who have not had coaching in fundamental movement skills, or who have not had the chance to develop expertise in sport-specific techniques, may be particularly vulnerable.

There is also emerging evidence in ballet and gymnastics to suggest that later maturing girls are more susceptible to growth-related injuries [31]. In many sports the demands of training increase with age and, thus, these athletes experience the growth spurt during a more challenging period of their development. Although the interaction between puberty onset and training load is only now being explored [40], there is some evidence that sudden increases in training intensity precedes traumatic contact, traumatic non-contact, and overuse injuries amongst 12-18 year old elite athletes participating in various sports [40]. This suggests that late developing athletes who encounter higher workloads during the peak of their growth spurt may indeed be at a disadvantage in terms of injury risk, which has implications for retention in elite sport pathways and possibly drop out from sport altogether.

5. Sport exposure and maturation

There has been some exploration of the effects of training on hormonal function and puberty onset. Specifically, it has been shown that menarche may be delayed by one to two years in some female athletes, but still typically falls within the normal range [41]. Yet, young female athletes who experience menstrual irregularity or dysfunction may be predisposed to overuse injury [1]. Menstrual irregularity can include amenorrhea (i.e., lack of menstruation by age 15), secondary amenorrhea (i.e., nine or fewer menses in the last 12 months post menarche), or oligomenorrhea (i.e., menses than are more than 35 days apart). A cross-sectional study of 249 female athletes in 33 sports reported that the prevalence of injury was higher in athletes who reported menstrual

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irregularity than athletes who reported normal menses [42]. This is of particular importance when considering that menstrual irregularity is a marker for Relative Energy Deficiency in Sport (RED-S), which is common in youth sport [41]. Young athletes who have lower body fat and are managing stresses associated with training, sport-specific demands, and insufficient nutritional strategies are at particular risk of developing this condition, and it may increase their likelihood of injury [41]. Therefore, sport in itself may present a challenge to the young female (endurance) athlete, with implications for immediate and long-term health.

6. Psychosocial development and health outcomes

A final development-related consideration is that young athletes are not only maturing physically, but cognitively and socially. The ability to regulate emotion and evaluate situational risk evolves through adolescence and into young adulthood, meaning that youth may not consider the consequences of their behaviour in the context of sport. For example, attempting to execute skills beyond one's capability has been explored as a significant factor in skiing and snowboarding injuries, as have peer pressure and risk-seeking behaviours [43]. Findings have been mixed, but there is some indication that youth tend to incorrectly perceive injury risk in various sports and may be unaware or unconcerned about potential long-term consequences [44]. Over-estimation of one's ability and feelings of invulnerability, as defining qualities of adolescence, have also been associated with sport injury [44]. This may extend to unwillingness to report injury and poor adherence to rehabilitation [45], which can increase the risk of negative long-term outcomes. Yet, despite the intuitive link between psychological development and sport injury, evidence supporting such relationships is limited and significantly underrepresented in the literature.

Moreover, the process of identity formation is a central feature of the adolescent time period. Athletic identity, defined by the extent to which being an athlete dominates an individual's self-perception and social roles, often develops for youth who spend a significant amount of time engaged in sport activity [46]. This can be facilitative for sport achievement and maintained

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physical activity participation, as athletic identity drives the pursuit of sport-related goals. However, it has been shown that those who develop a strong and exclusive athletic identity may be at increased risk of injury, as the desire to compete may override pain, fatigue, or medical advice and prompt continued participation to the point of injury (or whilst injured) [47]. Research in this area has been limited, but there have been small associations found between athletic identity and overtraining syndrome ($\beta = 0.118$, $p = 0.003$, $R2 = 0.12$) and injury incidence ($\beta = 0.119$, $p = 0.03$, $R2 = 0.13$) in adult samples [48]. Furthermore, both low (below the 25^{th} percentile) and high (above the 75^{th} percentile) levels of athletic identity have been shown to influence injury risk in elite adolescent ice hockey [49]. Strong athletic identity is a precursor for pursuing sport to the detriment of one's wellbeing [47], and as such may pose a threat as a factor that both leads to self-selection into sport and results from exposure to sport. It is therefore a salient concern in the context of sport specialization and its impact on the MSK health of the developing athlete.

7. Early sport specialisation

Alongside the professionalization of sport, there has been a concomitant trend for youth to become specialized early in their careers. Regardless of disagreements over definitions, the term 'sport specialization' generally refers to intense, year-round training in a single sport to the exclusion of others [50]. This typically increases with age through adolescence, but in some settings can begin in early childhood. In a sample of 1200 American athletes aged 7-18 years, it was estimated that 30% were highly specialised [51]. Many authors suggest that such high proportions may be most common in the USA, driven largely by the college scholarship system [52]; however, the idea of sport specialization is typified by the 'Academy' system, whereby young athletes are selected to join elite development pathways affiliated to professional teams. This structure aims to nurture young talent and retain the best athletes through to the time that they can be contracted to the club. This approach is most notably employed in European soccer, where those with predicted

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potential for elite performance are enrolled in the Academy as young as nine years old and spend approximately 11 months of the year training to become first team players [53].

The rationale behind early specialization is to provide talented athletes with access to better coaching and resources in order to support their development through intensive, dedicated training [54]. Undoubtedly, some degree of specialization is necessary for an athlete to achieve elite levels, and for early-entry sports, such as gymnastics, figure skating, and swimming, early specialization may be necessary [1,50]. Yet, there is contradictory evidence regarding the outcome of this approach, and when or if it is necessary for success [50]. Moreover, despite the number of young athletes who train to become professional, only a tiny fraction ever 'make it'. By requiring focus on a single sport, specialization disadvantages most youth who will never be elite at the expense of more general physical activity and the enjoyment of multiple activities. Indeed, given the risks associated with such practices for the gain of relatively few athletes, many national and international organizations have taken a stance against specialization in youth sport. In 2015, the International Olympic Committee released a consensus statement on youth athletic development that highlighted the risks associated with early specialization [41]. Specifically, it noted that youth athletes are at significant risk of overuse injury and other health issues (i.e., burnout, RED-S) when in a specialized environment. This aligns with the position statements of several other sport bodies [i.e., American Medical Society for Sports Medicine (AMSSM), National Basketball Association (NBA)] [1,55], whose recommendations generally cover two major areas relevant to MSK health: overuse injury and the benefit of motor skill development for lifelong physical activity.

Despite featuring centrally in most early specialization position statements, the effects of intensive training on injury are not well understood. In one of the largest studies on the topic, Jayanthi and colleagues explored the influence of specialization, training volume, and growth rate on injury in a sample of 7-18 year old athletes [51]. This case-control study included injured athletes who reported to a sport medicine clinic (cases; n = 846) and uninjured athletes undergoing sport medical screens at an affiliated clinic (controls; n = 368). After adjusting for age and hours per

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week of sport participation, sport specialization was an independent risk factor for overuse injury (OR = 1.27, 95% CI: 1.07, 1.52). Injured athletes also reported more total weekly sport and physical activity time [51]. Importantly, this study found that specialized athletes were not at an increased risk of acute injuries, confirming that overuse injuries represent the greatest injury burden in this population.

This study was part of a recent systematic review investigating the risk of overuse injury associated with early specialization [56]. Three studies were included in total, comprising a range of youth sport populations. The odds of increased injury risk for specialized athletes ranged from OR = 1.27 to 4.0, depending on sport and pathology. Patellofemoral pain, patellar tendinopathy, and Osgood-Schlatter's disease were the most commonly reported diagnoses but their association with specialization was modest at best, given the limited amount of primary data available and the varying quality of the included studies [56]. This review, although small, highlights that current evidence is based mostly on retrospective studies. Prospective designs may be more appropriate to detect injuries with gradual onset, but to date such studies have been sparse. Those that have been published have established loose but indicative associations between intensive training and overuse injury in youth cohorts [56].

The predominant mechanism of overuse injury is poorly managed training load [50]. For adults, a clear link between training load and injury has been established. Both too much and too little training are consistently associated with increased risk, as are acute spikes and low chronic loads during the season [57]. In youth populations, however, the evidence is less clear. Some studies have reported linear increases in injury risk with higher loads, prompting a commonly-held maxim that players should train no more hours per week than their current age [51,58,59]. This is based on one study that demonstrated a sharp increase in injury risk past 16 hours of weekly training across a variety of high school sports [60]. Conversely, other studies have shown no association between higher training loads and injury [40,61,62]. Further, Theisen et al. outline the potential importance of sport type, reporting that a higher number of competitions per 100 days

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were positively associated with injury in team sports, yet negatively associated with injury in individual sports [63]. Given such conflicting findings, there is insufficient evidence that the load-injury relationship differs between youth and adult athletes, or what the optimal training zone might be for athletes who are or are not in the midst of vulnerable developmental periods [57].

Mechanistically, the immature musculoskeletal system has limited ability to absorb and adapt to mechanical loading [64]. Apophyseal and epiphyseal plate injuries are generally prevalent during the early phases of puberty, but their risk is exacerbated by high training loads and frequent submaximal loading during repetitive sport-specific skills [1,64]. Without exposure to variable movement patterns, single-sport athletes are therefore at increased risk of overuse injury during periods of growth, particularly if training volume, intensity, and/or focus is not adjusted during vulnerable periods [1,64]. For example, Little Leaguer's shoulder (a repetitive stress injury at the proximal epiphysis of the humerus) is common to youth baseball pitchers [34]. Increased humeral retroversion and effort thrombosis have also been reported in this population, related to repetitive overload of the pitching arm [64,65]. Moreover, athletes learning specific techniques may be at increased risk of injury. Poor mechanics during baseball/softball pitching [65], cricket pace bowling [66], and rugby tackling have been implicated in both overuse and acute injuries, most notably in rugby union where better skill proficiency has been identified as protective against match injuries in U18 tournaments [67]. The combined effects of asynchronous growth and awkwardness, highly variable technique performance, and repetitive loading make developing athletes particularly susceptible to both skeletal and muscular injury. This presents unique challenges when managing training load and speaks to the necessity of individualized coaching focus when introducing complex or highly refined movement skills.

There is further evidence that high repetitive loads may lead to morphological changes in skeletal structures [66,68]. A study of twenty Academy rugby union players (mean age 21 years) reported that 95% presented with significantly reduced hip range of motion and abnormality on MRI, with evidence of labral pathology and chondral wear in a majority of cases [69]. This was

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attributed to repetitive sport-specific movements under high load over time. Furthermore, in both youth soccer and ice hockey, it has been shown that altered neuromuscular control and external rotation required by sport-specific skills can, under conditions of high load, result in CAM deformities and increased incidence of femeroacetabular impingement (FAI) [70]. Although evidence in this area is limited and there are mixed findings [71], a recent review found that there is higher prevalence of FAI in young male athletes training a minimum of three times per week, compared to non-athletic controls [68].

Although from a MSK perspective, load is often conceptualized only in terms of physical or mechanical stress applied to the body, it can be operationalized as having both 'external' and 'internal' components. External load refers to the training stimulus applied to the athlete, while internal load refers to the physiological and psychological response to that load [72]. Importantly, internal loads can be affected by non-sport factors such as life events and fatigue, even when external loads are unchanged [1,64] It is the balance of both components that leads to either functional adaptation or athlete burnout, the hallmark symptoms of which include poor performance, chronic muscle and joint pain, weight loss, increased resting heart rate, and frequent illness. This is a major source of sport drop out in youth age groups and therefore represents a significant challenge to long-term physical activity and MSK health.

Reduced motor skill development is a second major concern with specialized youth sport. With constrained focus on a particular set of movement patterns, athletes can develop asymmetries that may predispose to injury [73]. Although there is conflicting evidence around the asymmetry-injury relationship [74,75], and the predictive ability of common screening tools has been heavily questioned [76], preliminary evidence suggests that bilateral lower limb strength imbalances become exaggerated in early adolescence [77]. In a study involving 105 male soccer players from the English Premier Academy system, it was shown that bilateral ground reaction force asymmetry peaked between 13-15 years of age (11-13% difference) [77]. Furthermore, the study demonstrated

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that differences between dominant and non-dominant legs increased following peak height velocity, corresponding with the increased injury risk seen during periods of rapid growth.

Narrowly focused motor development can also influence future sport involvement. Variability typically introduced through participation in a variety of sport and recreational pursuits promotes more general movement competency that enables the individual to take part in a greater breadth of physical activity [78]. Early sport specialization does not allow for this and may leave participants without the requisite abilities to perform safely and successfully in other domains. Furthermore, the development of non-sport specific fundamental movement skills is associated with increased cardiorespiratory fitness and positive weight status through childhood and adolescence [79]. This highlights a distinct benefit of multisport participation during the developmental years, especially at recreational levels. Therefore, in the interest of keeping young athletes healthy and active, many organizations such as the National Association for Sport and Physical Education Guidelines for Participation in Youth Sport Programmes have recommended delaying sport specialization until youth have developed key fundamental movement skills that will facilitate more general physical activity engagement through adolescence and into adulthood [78].

Early specialization has regularly been criticized for triggering athlete burnout and dropout, which has knock-on effects for both sport performance and lifelong exercise motivation. Indeed, there is an estimated sport attrition rate of 70-80% amongst specialized adolescent athletes before the age of 15 years [54]. Consequently, and considering its myriad health implications with few demonstrable performance benefits, there are consistent recommendations from governing bodies and medical associations to delay or avoid sport specialization [1,41,55,80]. This, however, is inconsistent with current sport development pathways. Therefore, for those who are involved in intense single-sport training, coaches and practitioners are advised to allow periods of rest, to monitor training load particularly during periods of intense MSK growth, and to include periodized movement skill training to offset sport-specific demands [41,55,80,81].

8. Multi-sport youth athletes

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As with specialized athletes, there are challenges in protecting the health of those who compete in multiple sports. Load management becomes increasingly important, particularly when the training regimes of different coaches or teams are not synchronized or complimentary, and communication between those settings may not exist. For paediatric athletes, load management must also account for physical education classes and, depending on age, free play activities. There is currently no substantial evidence indicating increased injury risk for multi-sport compared to single sport athletes, but there are implications for the way that MSK injuries are managed in this population.

For the medical team, decision-making for single and multi-sport athletes is the same when assessing health risk but there are differences in the assessment of risk tolerance. Imagine, for example, a 15-year female athlete who is undergoing rehabilitation for a left lateral ankle sprain. The primary health risk assessment is focused on tissue health, and patient demographics, previous medical history, symptoms, signs and special test results would be contextual to the individual, not the sport. The assessment of activity risk, however, is where the complexity of the decision making process emerges. If the athlete plays both basketball and rugby, there are additional factors to consider. While limb dominance may remain the same, the type of sport, playing position, level of competition, as well as permissible and preferred protective equipment will likely all differ between sports. Though there may be some overlap in functional tests that could be used to assess rehabilitation progress, the number and diversity of sport-specific tests will need to increase to inform appropriate return to sport. Psychological readiness will also need to include a measure of sport specificity.

Assessing risk tolerance will also be more challenging when dealing with a multi-sport youth athlete. Many of the salient components (i.e., timing in season, internal and external pressure, injury masking), will differ, as will the expectation of various stakeholders, between sport settings. Additionally, there may be contradictory indications for return to sport, depending on the injury and nature of the competitive environment. For example, an athlete may be ready to return to a non-

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collision sport before being cleared for full contact. Anticipated training loads will influence return to sport strategies as well, especially for athletes who are approaching or in the midst of a growth spurt which may in itself present an injury/re-injury risk. Practitioners need to be aware that there is a significant gap in sport injury and rehabilitation research regarding return to performance outcomes for multi-sport athletes. Thus, the onus falls to the health care provider to cultivate an outcome profile that is informed by available evidence, clinical/technical training, and the experiences of their patient.

9. Injury prevention

A number of strategies have been proposed to mitigate injury risk and maintain overall MSK health in youth sport. These include limiting participation time and reducing sport-specific repetitive movements, scheduling rest and time away from sport, monitoring growth and maturation to create bespoke training programmes, and various nutritional strategies to promote bone health [1,41]. Unfortunately, as is the case across much of the injury prevention literature, there is a dearth of evidence regarding the application and ultimate effect of introducing such interventions in real-world settings. Similarly, rule changes at regional, national, or international level have also been widely proposed but sporadically trialled and rarely evaluated [41]. One exception is the national-level change to body-checking policy in youth ice hockey across North America, where meta-analysis evidence has shown a two- to four-fold decrease in game injury and concussion, respectively [41]. However, like many interventions, this addresses a unique challenge in a particular sport and as such its success may be context-specific. Therefore, despite widespread acknowledgement of the need for primary prevention to keep young athletes healthy and engaged, there are very few evidence-based options for practitioners to adopt in daily practice.

There are, however, two interventions that have gained widespread interest across the youth sport community: neuromuscular training (NMT) and bio-banding. Whilst NMT is supported by more than a decade of high quality research [82], bio-banding is relatively new and, although intuitively appealing, does not yet have a substantial evidence base to draw from. However, both

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approaches directly target identified growth and maturation-related injury risk factors and therefore present interesting case studies along the continuum from intervention design through implementation.

Neuromuscular Training

Broadly, NMT (a.k.a. integrated neuromuscular training, or INT) involves various strength, balance and coordination exercises that are delivered as a periodised programme with the aim of reducing injury risk and/or enhancing motor skills [52]. These programmes typically take the form of a warm-up routine, but may also be delivered as part of an overall fitness regime. With a focus on proprioception and balance, and emphasis on safe technique and joint alignment, such programmes have been shown to significantly reduce injury risk in team ball sports and multi-sport settings by between 28% and 80% when completed at least twice per week [41]. In a meta-analysis of 25 studies that examined NMT in youth sport, Emery and colleagues reported a 36% reduction in lower extremity injury risk and a compelling (though not statistically significant) 26% reduction in knee injuries specifically [82]. Most notably, the authors highlight the consistency of these findings across age groups and sports. The initiation of NMT programs may be most impactful in pre- or early adolescence, however, before risky movement patterns develop [83]. On the strength of existing evidence, several sport governing bodies and medical associations now advocate NMT as a standard component of youth sport participation.

Though in most instances NMT is implemented in team sport settings, there is a rationale for incorporating it into school physical education classes. It has been suggested that children with low movement competency and poor cardiovascular fitness are the most at risk of injury, and intervening in schools may be the best way to reach the largest susceptible population [52]. It is also a means of accessing those who compete in sport but might not use NMT as part of their training programme. Although this approach is only now being explored, preliminary evidence is promising. In a pilot cluster-randomized controlled trial, Richmond et al. investigated a 12-week high-intensity

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NMT program delivered as a warm-up in the first 15 minutes of school PE classes [84]. Students (aged 11-15) who participated in the programme had a significantly reduced risk of sport injury (IRR = 0.30, 95% CI: 0.19, 0.49). There were also positive changes in waist circumference (-0.99cm; 95% CI: -1.84, -0.14) and indirect measures of aerobic fitness in the intervention group [84]. Using a similar approach, Faigenbaum and colleagues reported that younger students (mean age 7 years) had singificantly improved fitness outcomes (i.e., push-up, long jump, and running performance) after engaging in a 15-minute NMT warm-up in their PE classes twice per week [85].

As with all injury prevention initiatives, NMT relies on a dose-response relationship: people have to continue using it to maintain its effects. Whilst uptake in the sport community has been suboptimal [86], there is appetite amongst school stakeholders to integrate NMT into the curriculum [87]. Trials are now underway to determine the feasibility and effectiveness of more widespread implementation [87], but there is every indication that this has potential to yield a considerable benefit to MSK health at a popluation level. This would extend protection to youth athletes who may not otherwise engage in NMT and promote healthy physical activity participation for a broad cross section of adolescents.

Bio-banding

The English Premier League is one of the top soccer leagues in the world. Recognising the need to understand child growth and development in order to optimise athletic performance and prevent injury, they recently launched an initiative to improve the assessment and monitoring of maturation across their professional soccer academy system as part of the Elite Player Performance Plan [https://www.premierleague.com/youth/EPPP]. This involved a series of educational workshops for academy staff to upskill sports science and medical practitioners on current best practice assessments. To aid staff in this process, they also modified the Premier League Player Management Application (PMA) to enable staff to better assess and monitor player growth and maturation. The PMA now allows staff to identify which players are early, on-time, and late

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maturing, and take these factors into consideration when evaluating fitness, predicting future growth status, and identify when players are entering different phases of development.

Armed with these resources, academies are now experimenting with innovative strategies, such as bio-banding, to optimise athlete development [88]. Through adolescence, athletes who are the same age can differ significantly in terms of height, weight, strength, and other markers of physical development that confer marked competitive advantages [16]. Bio-banding is the practice of grouping players on the basis of growth and maturation stages, rather than chronological age, to negate some of these effects. For example, instead of a traditional U14 training group, early maturing younger players might train with later maturing older players to create a more evenly matched cohort [89]. It should be noted that bio-banding is considered an adjunct, not a replacement, for age group competition, but is being explored as a means to manage training load and promote skill development for players with similar physical and psychological attributes.

The process of grouping players on the basis of a combination of age and physical criteria is common in a number of combat (e.g., judo, taekwondo, & boxing) and, to a lesser degree, contact sports (e.g., American football, rugby league) where extreme differences in size have implications for athlete safety competition equity. Research pertaining the potential benefits of bio-banding is limited, though emerging evidence in soccer suggests that it can benefit both early and late maturing players by encouraging a less physical and more technical style of play [88]. Competing against older and physically matched peers, early developers are no longer able to rely on their physicality and have to use their technical and tactical skills in order to succeed. Conversely, later maturing players have more opportunity to adopt positions of leadership and demonstrate their technical and tactical abilities. The impact of bio-banding practices upon injury risk during competition is lacking, though in soccer it has been reported that early and later players perceived lower risks of injury in bio-banded scenarios [88].

Bio-banding can also be used to identify and accommodate athletes entering developmental stages in which they are more susceptible to injury. According to the Premier League PMA, the

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practitioner should monitoring growth, performance, injury history, and symptomology more closely during phases of accelerated growth and, if there are concerns, reduce training load [17]. Practitioners working with athletes during these stages should also place greater emphasis on activities that enable the athlete to re-learn fundamental (i.e., running, lifting, and landing mechanisms) and sport specific skills, build strength, and maintain coordination and flexibility [89]. Bio-banding allows athletes to transition between groups depending on situational factors, thereby providing a flexible solution to managing the challenges of adolescence whilst preserving the educational component of the training environment.

Although bio-banding is a relatively new concept and consequently suffers from limited supporting evidence, it has substantial buy-in from the youth sport community [89]. This is a crucial first step toward success, as this is a complex environment with multiple levels of influence over practices and policies that affect athlete wellbeing. Unlike adults, who are able to make independent, informed decisions about sport participation and health behaviours, youth athletes often do not have the awareness or autonomy to do so. They generally rely on parents, coaches, referees, medical practitioners, schools, and governing bodies to act in their best interests. Therefore, implementation strategies must target multiple stakeholder groups, yet be intuitive and appealing to the athlete group they aim to protect. Unfortunately, without policies to enforce them, prevention programs typically see poor to moderate levels of use [41]. This tends to be sport-specific and depends largely on organizational factors that are unique to the immediate context [41]. Research has also found that coaches and parents often exhibit deficiencies in knowledge and injury prevention behaviours, which inhibit the translation of evidence into practice [41]. Considerable effort has been put into the content and delivery of injury prevention programs to overcome these issues, but to date most efficacious interventions have yielded lower public health impact than could be expected and injury remains a salient concern in youth sport.

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10. Injury rehabilitation

Given the nature of youth sport, completely eliminating risk is an unrealistic goal. Accordingly, age appropriate rehabilitation techniques are necessary for promoting recovery and preserving overall MSK health. Although clinical approaches will be governed by injury type and other related considerations, there are some features of the athlete-practitioner relationship that are unique to the youth setting and should be acknowledged for their potential to influence patient outcomes.

There are different settings in sport for healthcare providers. Those who work embedded in the daily training environment have the most opportunity to customize management programs according to the daily needs of their athletes. This includes the rehabilitation process, where they can get feedback from the athlete, coaches and parents and monitor adherence to prescribed treatments. Clinicians doing event coverage may have a short-term opportunity to provide that level of care, but will also need to develop and communicate a continuance of care plan for the athlete in their home location. Finally, there are clinicians who see athletes in the office setting. Here, observations are limited to a setting unlike the athlete's field of play, and the information obtained to facilitate decision-making will be based primarily on reports from the athlete and/or their parents, potentially compromising return to play decisions. In addition, factors such as financial resources and transportation have more influence when managing the care of paediatric athletes, who are often constrained by academic (and parent employment) schedules. In many cases, treatment plans will depend entirely on the athlete and their immediate support network to implement without clinical supervision. All therapeutic relationships with youth athletes are complex, but the less interaction practitioners have with the athlete in the environment in which they train and compete, the more critical communication and interpersonal skills become. This is especially true when managing multi-sport athletes who must navigate the return to sport transition across different settings with influence from different, and possibly contradictory, stakeholders.

There are also unique ethical implications of providing treatment to young athletes. To illustrate, shared decision-making is addressed in the International Olympic Committee consensus

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statement on the prevention, diagnosis, and management of paediatric anterior cruciate ligament (ACL) injuries [90]. The position of the authors is that, due to the difficulties in securing legally legitimate informed consent from children, practitioners have a duty to serve the best interests of the child. The importance of gaining their assent, irrespective of parental wishes, is emphasized in line with their growing sense of autonomy [90]. This balance can become more difficult for an athlete who has a history of injury and from a clinical perspective is at high risk of recurrent or subsequent injury, or has a poor long-term prognosis. For practitioners, the decision to recommend that an athlete not return/retire from sport is difficult, and there are no objective criteria to inform when this decision should be considered. There are, however, ethical touch points that can be used to guide the decision-making process. These standards relate to athlete's best interests (e.g., "How are the athlete's best long term interests upheld by returning to sport?"), the harm principle (e.g. "Will the athlete be worse off by returning to sport?"), and the costs-benefits of a decision (e.g., "What are the costs and benefits that I need to consider in making the decision to return this athlete to sport?"). Thus, it is important that, while the athlete remains at the centre of all conversations regarding retirement, the clinician must be prepared to communicate the necessary information to both the athlete and their parent/guardian in a fashion that facilitates informed consent and understanding of whatever pathway is chosen.

Ultimately, the success of any rehabilitation plan depends on the athlete's willingness and ability to adhere to clinical recommendations and (non)return to sport guidelines. In this sense, ensuring athletes and parents understand not only the diagnosis and treatment options, but also the prognosis and long-term implications of injury, is key. Furthermore, communicating return to sport criteria and/or graduated return to play protocols to athletes, their parents, and coaches is a vital part of the process. Evidence-informed return to sport guidelines exist for paediatric concussion [91] and are beginning to emerge for other common youth sport injuries [92]. Return-to-learn recommendations are also gaining traction, particularly considering the cognitive load imposed by school on top of the demands of training and competing [93]. Previous injury is routinely shown to

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be the biggest predictor of subsequent injury in youth sport [94]; therefore, thorough rehabilitation and carefully managed return to sport are important for keeping athletes healthy and able to continue sport participation in the long term.

11. Sport and long-term MSK health

Evidence regarding the long-term outcomes of sport participation is surprisingly sparse, with few rigorous longitudinal studies. Systematic reviews have shown that general physical activity during adolescence is associated with a number of lifelong health benefits, including reduced central adiposity, cardiovascular disease risk, and cancer incidence [95]. Yet, markers of MSK health have received far less attention.

Bone health has been the most commonly examined MSK outcome, operationalized as bone mineral density (BMD), bone mineral content, bone mass, or bone geometry. The evidence suggests that there are benefits of physical activity for immediate and longer-term bone health amongst youth participants, and that exercise may help to optimise peak bone mass during the critical adolescent accrual period [95,96]. There is also weak evidence that youth physical activity may reduce fracture risk later in life, though this needs further investigation [95]. However, studies have also shown a moderate association between youth and adult physical activity levels, the indirect effect of which may be driving many of the observed health benefits associated with early participation. Moreover, a lack of high quality prospective designs limits the interpretation and generalizability of existing evidence, thereby inhibiting its clinical applicability [95].

Nonetheless, emerging sport-specific research supports the more general physical activity literature. Plyometric training and high-impact land-based youth sports have been associated with higher BMD and bone mineral content, and bone structure improvements which may be maintained for several years [97]. Multisport participation has been shown to improve bone geometry compared to low impact activities such as swimming and cycling [96]. Ball sports involving multidirectional

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loading of lower limb joints are particularly recommended for generating bone mass and some authors have speculated that they may be protective against future stress fracture under high-load conditions (i.e., distance running or occupational requirements) [98]. Muscular fitness derived from sport participation has also been related to bone health, with stronger youth athletes exhibiting better BMD and bone mineral content into adulthood than their less fit counterparts [99].

Conversely, there is some evidence that sport participation may be detrimental to MSK health. For example, young endurance athletes with high mileage training programs and low body mass are at increased risk of low BMD and recurrent stress fractures [41,96]. Though here is no evidence that repetitive loading leads to degenerative joint changes, young athletes who suffer a sport-related joint injury are more likely to develop early onset post-traumatic osteoarthritis (OA). In a historical cohort study, Whittaker and colleagues recruited 50 individuals aged 15-26 years old who had a sport-related intra-articular knee injury sustained in the previous 3-10 years and 50 uninjured age-, sex-, and sport-matched controls [15]. They found that the injured participants had poorer outcomes related to knee symptoms and knee-related quality of life [measured by Knee Osteoarthritis and Injury Outcome (KOOS) score], and were 3.75 times (95% CI: 1.24, 11.3) more likely to be overweight. In a subsample of 73 matched pairs, injured participants had 10 times (95% CI: 2.3, 42.8) greater odds of MRI-defined OA, suggesting that arthropathic changes that have lifelong impact on health-related quality of life may emerge as early as three years following a youth sport injury [100]. This study, though methodologically robust and suitably powered, represents only an initial investigation into this issue. Further research is needed to determine the typical progression of PTOA in young populations, to identify appropriate methods of diagnosis and management, and to understand the impact of early PTOA symptoms on lifelong MSK health.

12. Summary and conclusions

The World Players Association Declaration on Safeguarding the Rights of Child Athletes demands that stakeholders communicate to youth athletes all risks associated with a sporting career

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[http://www.uni-europa.org/wp-content/uploads/2017/11/Declaration_on_safeguarding_the_rights_of_child_athletes.pdf]; however, current understanding of youth sport outcomes is limited by a lack of longitudinal data. For informed decision making, this gap presents a significant challenge to young athletes and their families. Yet, there is strong evidence that sport participation through adolescence provides a number of measurable benefits, including overall physical fitness, improved bone health, and protection against future morbidity. Nevertheless, these benefits must be balanced with potential risks such as injury and its consequences for lifelong MSK health and physical activity.

Participation in youth sport is ultimately a value judgement. For some, the risks associated with injury will preclude certain sports, or sport altogether. For others, the benefits will outweigh these risks, and those with aspirations of achieving elite levels will see risks as an acceptable by-product of the athlete development process. The key in each scenario is ensuring that the athlete's best interests are protected. To this end, current evidence suggests that youth sport generally has positive effects on MSK health, but more emphasis must be placed on injury prevention, appropriate training load, and better injury management strategies to promote ongoing physical activity and long-term quality of life.

Practice Points

- Objective assessments of youth athletes' growth and maturity status should be taken regularly to help guide training practices
- Multi-sport participation should be encouraged as part of a healthy, active lifestyle through childhood and adolescence
- Practitioners should consider their responsibilities to the athlete's best interests when providing treatment and return to sport recommendations

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Research Agenda

- Longitudinal studies of youth athlete outcomes are needed to elucidate the life course impact of sport participation
- Better understanding of the interacting effects of maturation, training load, and sport type would help to inform decision making in the youth sport community

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