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# Advancements in Pediatric Sports Medicine: Addressing Injury Prevention and Rehabilitation in Youth Athletes

Riaz Ahmed

## ABSTRACT

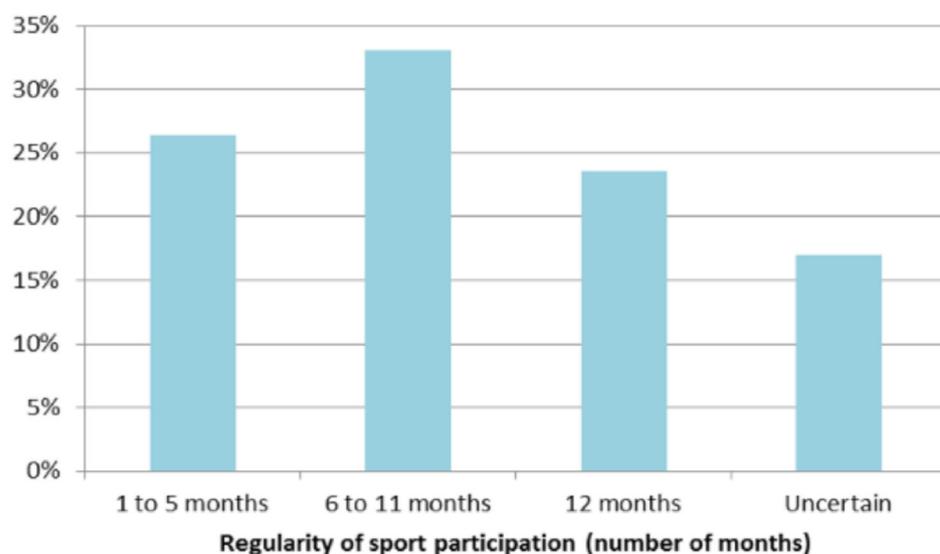
Due to the physiological, psychological, and other complexities involved in the development of young athletes, pediatric sports medicine is a distinctive field. This review synthesizes current evidence regarding injury characteristics among youth athletes, along with prevention and rehabilitation strategies. It finds that adolescents are more prone to overuse injuries and psychological challenges during recovery, while younger children are most vulnerable during informal play. Neuromuscular training, for example, has proven to be an effective prevention program; however, it remains insufficient for addressing the impact of sport specialization on injuries. It still fails to consider the long-term mental health effects of youth sports. Recovery after injury should integrate muscle repair with psychosocial support for athletes whose athletic identities are at risk. Emerging wearable sensor technologies hold promises for personalized monitoring, but barriers to implementation persist. This review underscores the importance of collaboration among clinicians, researchers, coaches, and parents in developing evidence-based care models tailored to specific age groups. Future directions include enhancing injury surveillance systems, advocating for pediatric-specific policies within sports federations, and acknowledging the significance of mental health recovery as equal to physical recovery. A multidisciplinary approach should be employed to optimize safety, performance, and long-term well-being in youth sports.

**Keywords:** Pediatric sports medicine, Youth athlete rehabilitation, Neuromuscular training, Wearable sensor technologies, Sport specialization risks

## Introduction and Background

The participation of children and adolescents in organized sports has seen a significant rise in recent years, driven by growing awareness of the physical and mental health benefits of regular physical activity.<sup>1,2</sup> According to the 2020 National Health Interview Survey (NHIS), participation in sports teams is linked to improved physical and mental well-being among youth. However, disparities persist across socioeconomic, gender, and racial subgroups.<sup>2</sup> In Canada, sport participation among children aged 5–17 rebounded to 68% in 2022, after a pandemic-related decline to 44% in 2021, highlighting the importance of structured physical activity in youth development (see Figure 1).<sup>3</sup> Similarly, Healthy People 2030 reports that 58.4% of U.S. children aged 6–17 participated in sports during the 2016–2017, underscoring the need for continued efforts to promote athletic engagement.<sup>4</sup> However, increased sports participation is associated with an increased risk of injury, and age-specific approaches to preventing and rehabilitating pediatric athlete injuries need to be developed to meet better the unique physiological and developmental needs of the growing athlete.<sup>1</sup> As young athletes, the growth and maturation process impact injury and recovery in pediatric athletes.

The significance is highlighted by the European Academy of Pediatrics (EAP) and the European Confederation of Primary Care Pediatricians (ECPCP) regarding the pre-participation evaluation (PPE) to determine fitness for sports, although there are no standardized protocols. Furthermore, socioeconomic



**Fig 1 | Regularity of sport participation**

Source: 2022 parent survey of the physical activity and sport participation among 5–7 year olds, CFLRI<sup>3</sup>.

factors also influence sports participation; children from higher-income families are more likely to join or engage in organized sports due to financial barriers such as equipment costs and membership fees.<sup>5</sup> As boys generally outpace girls, migration background does not appear to have an impact.<sup>5</sup> This indicates that providing equal access to sports programs and specific injury prevention strategies is essential for ensuring youths' long-term musculoskeletal health. Consequently, understanding common injury patterns, evidence-based prevention techniques, and rehabilitation protocols should be considered to foster development. Incorporating these considerations can aid healthcare professionals in enhancing pediatric athlete safety and promoting sustained sports participation.

### Research Objectives

- To evaluate the most common injury patterns in youth athletes and the physiological factors contributing to age-specific injury risks.
- To review evidence-based injury prevention strategies tailored for pediatric populations, including neuromuscular training, sport-specific modifications, and protective equipment.
- To explore the most recently updated rehabilitation protocols for children and adolescents, considering growth, psychological development, and return-to-sport readiness.
- To assess how gender, sport specialization, and socioeconomic factors influence injury risk and the outcome of injury recovery.
- To identify research gaps to refine knowledge of pediatric athlete factors that promote safety and long-term musculoskeletal health.

### Aims and Scope of the Review

This review examines injury patterns, prevention strategies, and rehabilitation protocols in pediatric sports medicine, focusing on the physiological and developmental factors unique to youth athletes. It examines evidence-based interventions, including neuromuscular training and sport-specific modifications, while addressing disparities linked to gender, sport specialization, and socioeconomic status. The scope also

encompasses return-to-sport readiness and long-term musculoskeletal health. This review is justified by the rising sports participation among children (68% in Canada, 2022)<sup>3</sup> and the need for equitable access, as socioeconomic status significantly impacts organized sports engagement.<sup>5</sup> By synthesizing current research, this review aims to inform clinical practice and guide future studies in optimizing the safety of pediatric athletes.

### Epidemiology of Pediatric Sports Injuries

Pediatric sports injuries demonstrate distinct epidemiological patterns influenced by age, sport type, and external factors like the COVID-19 pandemic (see Figure 2). During the strictest lockdown period (March-June 2020), orthopedic clinics reported only 257 pediatric sports injuries compared to 483 in 2018 and 444 in 2019, representing a 47–53% reduction in cases.<sup>6</sup> This dramatic decrease coincided with school and playground closures. However, the injuries that did occur showed notable differences: patients were younger (median age 11 vs. 13 years), more likely to be White (66.9% vs. 47.7%), and predominantly sustained fractures (83.7% of cases) requiring more surgical interventions (14.8% vs. 7.8% pre-pandemic).<sup>6</sup> Only 15.2% of 2020 injuries occurred in formal sports settings compared to 71.4% pre-pandemic, reflecting the shift to informal physical activity during restrictions.<sup>6</sup> In contrast, pre-pandemic data from U.S. high schools (2015–2019) reveals an overall injury rate of 2.29 per 1000 athlete exposures (AEs), with significant variations by sport and gender.<sup>7</sup> Football had the highest injury rate (3.96/1000 AEs), followed by girls' soccer (2.65) and boys' wrestling (2.36).<sup>7</sup> Male athletes showed consistently higher injury rates than females (2.52 vs. 1.86/1000 AEs), with competition injuries occurring 3.39 times more frequently than practice injuries.<sup>7</sup> The most common diagnoses were sprains/strains (36.8%) and concussions (21.6%), primarily affecting the head/face (24.2%), ankle (17.6%), and knee (14.1%).<sup>7</sup> Geographic studies reveal additional patterns.

In China's Xinglin District (2016–2019), younger children (0–4 years) predominantly sustained head injuries (41.13%) from falls (52.05%), while adolescents

	Pandemic	Prepandemic
"Sports-type" injury	6 (2.3)	146 (15.7)
Concussion	3 (1.2)	57 (6.1)
Patellar dislocation	1 (0.4)	31 (3.3)
Anterior cruciate ligament tear	1 (0.4)	28 (3.0)
Other knee ligament injury	0 (0)	16 (1.7)
Meniscus tear	1 (0.4)	9 (1.0)
Shoulder dislocation	0 (0)	5 (0.5)
Other injuries	251 (97.7)	781 (84.2)

<sup>a</sup>Values reported as n (%).

Fig 2 | Comparison of "sports-type" injuries during and before the COVID-19 pandemic<sup>6</sup>

(15–18 years) showed more extremity injuries from mechanical causes (36.42%).<sup>8</sup> Sports-related concussions in U.S. emergency departments demonstrated a significant 10-year decline (2013–2022), with football (23%) and soccer (9.6%) remaining leading causes but showing decreasing trends, particularly during the 2020 lockdowns.<sup>9</sup> Gender disparities persist, with males accounting for 65% of concussion cases, although female representation increased over the decade.<sup>9</sup> In a 2019 prospective study of adolescent athletes (14–21 years), key risk factors were identified, including excessive training hours (7.21 injuries per 1000 hours in soccer), inadequate warm-ups, and poor facilities.<sup>10</sup> The most frequent injuries were lumbar strains (12.24%), ankle sprains (11.98%), and fractures (9.31%), with 59.28% occurring during practice versus 40.72% in competition.<sup>10</sup> These findings demonstrate that pediatric sports injury patterns vary substantially by age, sport, setting, and socioeconomic factors, underscoring the need for tailored prevention strategies.

**Age-Specific Risk Factors of Pediatric Sports Injuries**

Pediatric sports injuries are significantly influenced by age-specific risk factors that vary across different developmental stages and levels of sport participation. With nearly 25 million children involved in school sports and 20 million in community-based programs in the U.S., sports-related injuries are the second leading cause of emergency room visits among youth.<sup>11</sup> Age-specific risk factors for pediatric sports injuries demonstrate clear patterns across developmental stages. In elementary school children (both lower and upper grades), weekly hours of sports participation and early sport specialization emerge as significant risk factors

for injury, with their interaction being particularly impactful in younger age groups.<sup>12</sup> As children progress to junior high and high school, sex differences become more pronounced, with female athletes at higher risk, along with those participating in high-level competitions and those with previous injury histories.<sup>12</sup> Maturation status significantly influences injury patterns, as shown by studies using the Tanner-Whitehouse III method, where less mature girls showed higher odds of strains and fractures than sprains. Simultaneously, boys aged 10–11 years demonstrated greater susceptibility to upper limb injuries.<sup>13,14</sup> The relationship between physical activity intensity and injury risk is particularly notable, with each additional minute of moderate-intensity activity increasing the odds of strains or fractures by 1.04 times relative to sprains, while each advancing year of bone age decreased these odds by 1.7 times.<sup>14</sup>

Concussion patterns show distinct age-related variations, with younger children (5–9 years, *n* = 164) more likely to sustain injuries due to changes in daily habits (yes = 40.9%), (no = 54.3%) and not reported (*n* = 4.9%) or sleep changes activities (yes = 46.3%), (no = 51.8%) and not reported (*n* = 1.8%) compared to adolescents (see Figure 3).<sup>15</sup> While younger concussed athletes typically present with fewer symptoms, they exhibit greater severity in somatic and emotional symptoms. They are less likely to report school-related difficulties (25.6%) or sleep disturbances (46.3%) than older peers.<sup>15</sup> The scale of youth sports participation in the U.S., with approximately 25 million scholastic participants and 20 million community-based participants, creates significant exposure to injury, making sports injuries the second leading cause of emergency

	All ( <i>n</i> = 3280)		5–9 Years ( <i>n</i> = 164)		10–12 Years ( <i>n</i> = 604)		13–18 Years ( <i>n</i> = 2512)		<i>p</i> -Values
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	
<b>Daily habits changes</b>									<0.001 <sup>b,c</sup>
Yes	1700	51.8	67	40.9	274	45.4	1359	54.1	
No	1413	43.1	89	54.3	294	48.7	1030	41.0	
Not reported	167	5.1	8	4.9	36	6.0	123	4.9	
<b>Sleep changes</b>									<0.001 <sup>b,c</sup>
Yes	1980	60.4	76	46.3	310	51.3	1594	63.5	
No	1192	36.3	85	51.8	267	44.2	840	33.4	
Not reported	108	3.3	3	1.8	27	4.5	78	3.1	

Note: <sup>b</sup> denotes a significant difference was detected between 10–12- and 13–18-year-olds; and <sup>c</sup> denotes a significant difference was detected between 5–9- and 13–18-year-olds. Daily habits changes included lightheadedness when standing up, increased/decreased appetite, increased/decreased urination, urination accidents, constipation, and diarrhea.

Fig 3 | Frequencies of clinical characteristics by age group<sup>15</sup>

department visits for children and adolescents.<sup>11</sup> Current estimates suggest 3 million annual emergency visits and an additional 5 million primary care or sports medicine clinic visits for youth sports injuries, though many more likely go unreported.<sup>11</sup> These findings collectively demonstrate that injury risks evolve through developmental stages, influenced by training volume, biological maturation, sport specialization, and prior injury history, highlighting the need for age-specific prevention strategies that account for these dynamic risk factors.

**Prevention Strategies in Pediatric Sports**

Effective injury prevention strategies in pediatric sports must address sport-specific risks while considering the developmental differences in young athletes. The FIFA 11+ Kids program has demonstrated particular success in soccer, reducing overall injury risk by 48% and serious injuries by 74% through structured warm-ups that incorporate balance, strength, and neuromuscular training.<sup>16</sup> Systematic reviews of over 10,000 young soccer players (ages 7–14) confirm these benefits, showing a dose-response relationship where increased weekly sessions enhance protection.<sup>16</sup> Beyond injury reduction, the program improves physical performance, with studies reporting significant gains in dynamic postural control (4.8–5.1 cm increase in Y-balance test reach), agility (0.5 seconds faster), and vertical jump height (3.1 cm improvement in countermovement jumps) after just 4 weeks of implementation (see Figure 4).<sup>17</sup> Younger children (9–12 years) show particular benefits in foundational capacities,

with the program increasing static balance by 8.23–8.70 points, dynamic balance by 5.24 points, and leg strength by 23.30 units on standardized tests.<sup>18</sup> For adventure/extreme sports, where injury rates are notably high, prevention requires tailored approaches addressing sport-specific mechanisms while considering youths’ risk-taking behaviors.<sup>19</sup>

Evidence suggests that multimodal strategies, which combine equipment modifications (e.g., protective gear) with environmental adaptations (e.g., safer terrain) and supervised progression of skills, effectively mitigate risks.<sup>19</sup> In netball, targeted programs following the TRIPP framework reduced ankle sprains—the most common injury, at 89.4 per 1000 player hours in pre-elite competitions—through neuromuscular training that emphasized landing mechanics and proprioception.<sup>20</sup> However, research gaps persist regarding optimal prevention for non-lower extremity injuries like concussions (12% of netball injuries) and back pain.<sup>20</sup> Key implementation challenges include ensuring program adherence and addressing developmental differences in responsiveness. The success of FIFA 11+ Kids stems partly from its integration into regular warm-ups, requiring minimal additional time.<sup>17</sup> Similar approaches may enhance uptake across sports by adapting exercises to athletes’ maturation levels (e.g., simplified versions for pre-pubertal children).<sup>16</sup> Ongoing monitoring remains critical, as evidenced by findings that 39% of recurring injuries in youth occur at previously injured sites.<sup>12</sup> Future prevention efforts should prioritize sports with the highest injury burdens (e.g., football, wrestling) while developing

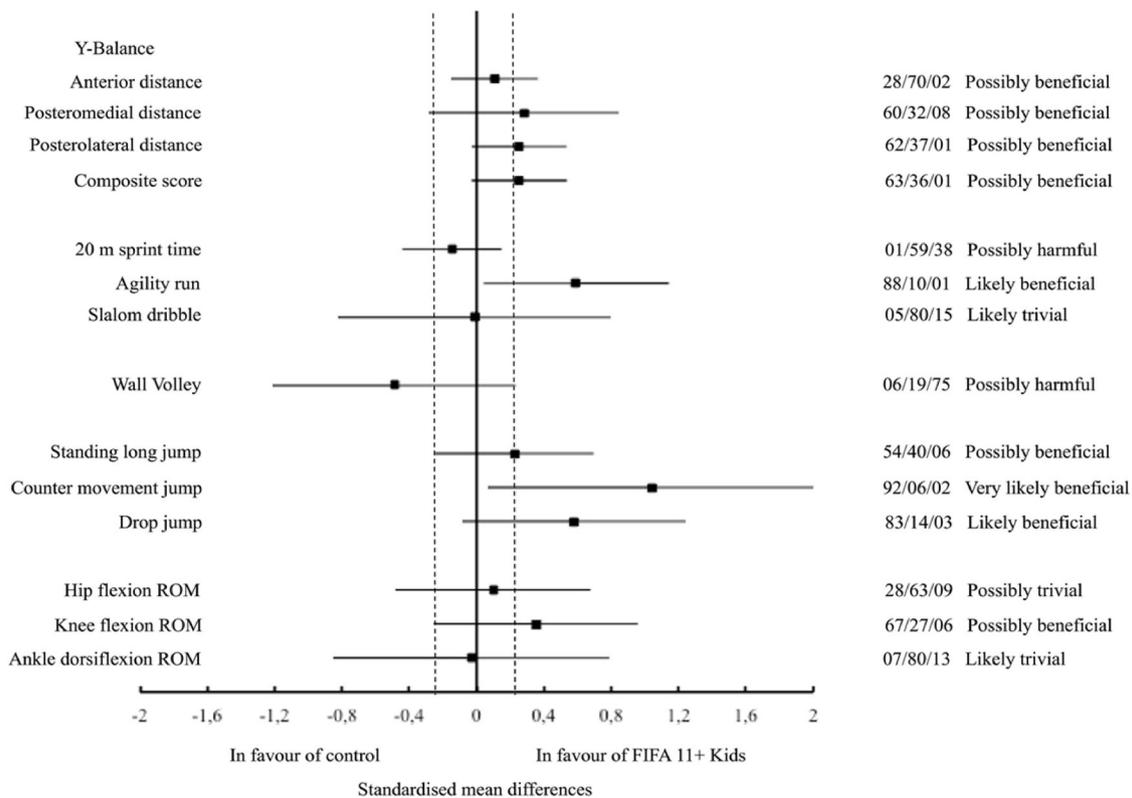


Fig 4 | FIFA 11+. Kids and control group<sup>17</sup>

age-appropriate versions of proven programs for broader adoption.

### Rehabilitation and Return-to-Sport Protocols (RTS)

RTS protocols for pediatric athletes must address both physical recovery and psychological readiness, with significant differences observed across age groups. Following ACL reconstruction, pediatric patients (ages 11–15) demonstrate superior recovery outcomes compared to adolescents and young adults, with 70% returning to knee-strenuous sport at 8 months versus 39% of adolescents and 35% of young adults.<sup>21</sup> By 12 months post-surgery, these rates increase to 90% for pediatric patients, compared to 71% for adolescents and 62% for young adults.<sup>21</sup> Figure 5 depicts that ‘pediatric patients had the largest proportion of patients achieving an LSI 90’ at the 8-, 12-, and 18-month follow-ups, followed by adolescents and young adults with the smallest proportion of patients achieving an LSI 90’. Younger athletes also report higher psychological readiness scores on the ACL-Return to Sport after Injury (ACL-RSI) scale and greater self-efficacy (as measured by the Knee Self-Efficacy Scale), suggesting age-related advantages in coping with rehabilitation stressors.<sup>21</sup> However, adolescent athletes frequently face psychological barriers during recovery, including fear of reinjury (reported by 100% of high school athletes in qualitative studies), persistent uncertainty about recovery, and negative social comparisons from coaches or parents.<sup>22</sup> These psychosocial factors often outweigh physical limitations as the primary obstacles to RTS, with ACL-RSI scores indicating that emotional responses (e.g., anxiety) are stronger predictors of RTS success than performance confidence.<sup>23</sup>

Psychological interventions, including stress management, cognitive restructuring, and mindfulness, have demonstrated efficacy in improving rehabilitation adherence and outcomes in junior athletes.<sup>24</sup> Peer mentoring programs show particular promise in mitigating isolation during recovery, as adolescents report feeling more motivated when connecting with others who have undergone similar injuries.<sup>22</sup> Importantly, sports injuries in adolescence profoundly affect identity development, with many athletes struggling to maintain self-confidence when unable to participate.<sup>25</sup> Current protocols increasingly emphasize holistic approaches that integrate sport psychology techniques (e.g., motor imagery, social support) with physical rehabilitation to address these multidimensional challenges.<sup>24</sup> While pediatric patients exhibit faster physical and psychological recovery trajectories, all youth athletes benefit from structured, phased RTS protocols that monitor both functional milestones (e.g., muscle symmetry) and psychological readiness indicators (e.g., ACL-RSI scores  $\geq 71$ ).<sup>21,23</sup> It needs to focus on developing age-specific psychological interventions to optimize recovery across developmental stages.

### Psychosocial Aspects and Long-Term Impact of Pediatric Sports Injuries

Pediatric sports injuries extend beyond physical consequences, significantly affecting young athletes’ psychosocial well-being and long-term mental health. Adolescent athletes face unique challenges during injury recovery because sports participation is a crucial outlet for emotional development, social connection, and identity formation.<sup>26</sup> The abrupt removal from athletic participation due to injury can trigger emotional

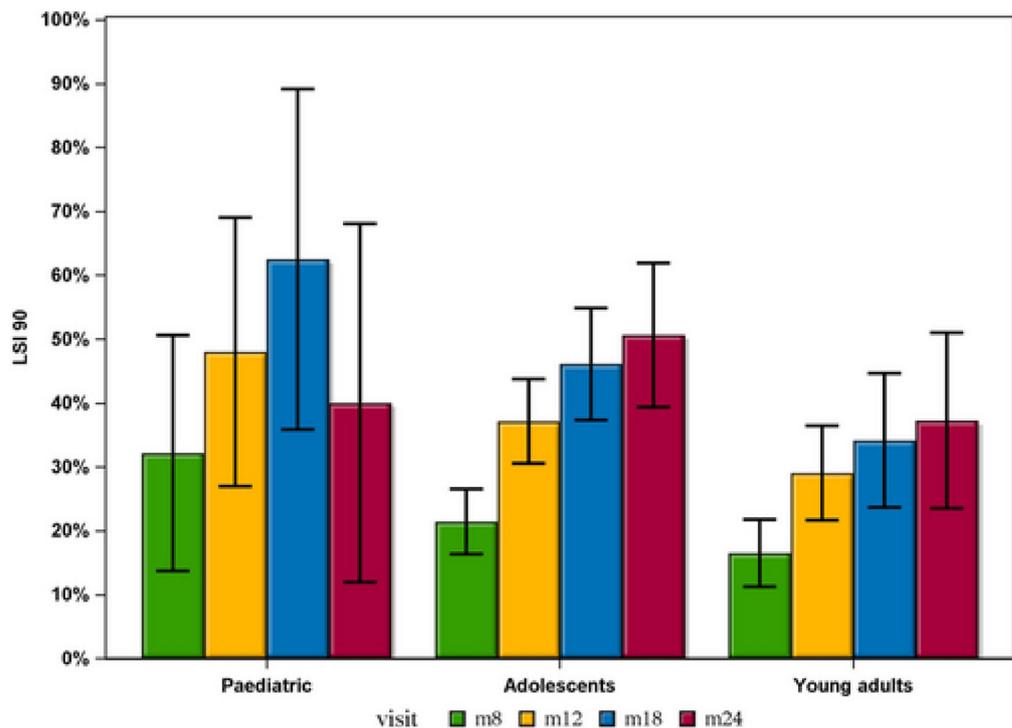


Fig 5 | Proportion of patients achieving an LSI 90<sup>21</sup>

distress, with studies demonstrating increased risks of anxiety, depression, and social isolation, particularly among specialized athletes who derive substantial self-worth from sports.<sup>27</sup> Sport specialization introduces compounding psychosocial risks, as intensive training regimens (often exceeding 20 hours weekly) correlate with 42% higher burnout rates, decreased academic performance, and disrupted sleep patterns compared to athletes participating in multiple sports.<sup>28</sup> The Figure 6 represents the ‘relationship of sport specialization in young athletes and its association with mental health, sleep, the drive for success in sport, and burnout’.<sup>28</sup> These effects frequently persist beyond physical recovery, with injured athletes reporting lingering fears of reinjury (68% in collegiate samples) that may permanently alter their sports participation patterns.<sup>29</sup> The mental health impacts vary by developmental stage, with younger athletes (ages 11–14) demonstrating greater emotional resilience but increased dependence on parental support systems during rehabilitation.<sup>26</sup>

Conversely, older adolescents (15–18 years) exhibit higher rates of athletic identity foreclosure, where self-concept becomes disproportionately tied to sports performance, which occurs in approximately 30% of specialized high school athletes.<sup>27</sup> This over-identification predicts poorer psychological adjustment to injury, including maladaptive coping behaviors like premature return-to-play or training through pain.<sup>30</sup> Consensus guidelines emphasize multidisciplinary management, incorporating mental health screening, with team physicians recommended to monitor for warning signs, including sleep disturbances (more than four nights per week), academic decline (more than one letter grade), or social withdrawal (lasting more than 2 weeks).<sup>30</sup> Longitudinal studies reveal concerning legacy effects, with former

youth athletes reporting elevated rates of chronic pain (22%), activity avoidance (18%), and clinical anxiety (12%) up to 5 years post-injury.<sup>29</sup> Early specialization compounds these risks, as single-sport athletes demonstrate a 2.3 times greater likelihood of sport abandonment by age 17 than multi-sport peers.<sup>28</sup> Current best practices advocate for integrating proactive mental health support throughout rehabilitation, including cognitive-behavioral strategies to rebuild confidence and peer mentoring programs to maintain social connections.<sup>26</sup> However, significant research gaps remain regarding optimal interventions for vulnerable subgroups, particularly female athletes and those from low socioeconomic backgrounds who experience compounded stressors.<sup>29</sup> Future efforts can prioritize psychological outcomes with equal vigor as physical recovery in youth sports medicine protocols.

### Current Debates and Research Gaps

Significant knowledge gaps persist in pediatric sports medicine, particularly long-term rehabilitation outcomes. The current literature lacks robust longitudinal studies that track recovery trajectories beyond 2 years post-injury, limiting our understanding of the lasting musculoskeletal consequences.<sup>21</sup> Debate continues around optimal return-to-play (RTP) timelines, with existing protocols often extrapolated from adult populations despite developmental differences in healing rates and psychological readiness.<sup>23</sup> The absence of consensus is particularly evident in ACL rehabilitation, where evidence-based guidelines for pediatric patients are underdeveloped compared to those for adults.<sup>21</sup> Furthermore, current prevention and rehabilitation strategies frequently overlook gender-specific physiological differences and varying maturation rates, despite studies showing girls’ two to eight times higher ACL injury risk during puberty.<sup>27</sup> Research also inadequately addresses socioeconomic disparities, with underrepresented populations constituting less than 15% of participants in major pediatric sports medicine studies.<sup>26</sup> This gap obscures potential barriers to care access and adherence in low-income communities. Furthermore, while the risks of sport specialization are well-documented, few interventions target its psychological impacts, such as burnout and identity foreclosure.<sup>27</sup> Emerging discussions highlight the need for standardized mental health screening tools specific to injured young athletes, as current protocols primarily assess physical recovery markers.<sup>29</sup> These collective gaps underscore the need for large-scale, longitudinal studies that incorporate diverse populations and consider developmental aspects to establish evidence-based guidelines tailored to the unique needs of pediatric athletes.

### Future Directions for Pediatric Sports

Emerging wearable technologies show significant promise for advancing pediatric sports medicine through real-time biomechanical monitoring and injury prevention. Recent studies have demonstrated that inertial sensors and EMG devices can effectively track joint angles (mean:  $112.3 \pm 6.8$ ), muscle activation

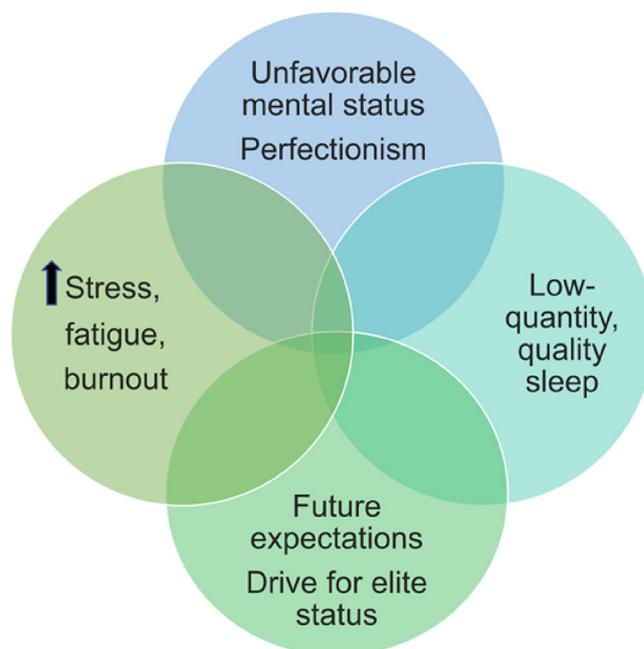


Fig 6 | Psychosocial relationships in the sport specialization of young athletes<sup>28</sup>

(43.2% ± 4.5), and workload metrics in young athletes, enabling the early identification of injury risks.<sup>30</sup> These systems are particularly valuable for developing maturation-specific training programs, as they capture developmental variations in movement patterns that traditional assessments may miss.<sup>31</sup> School-based implementation of such technologies could revolutionize injury surveillance, with studies reporting over 26 successful interventions using Fitbit and ActiGraph devices across 14,852 pediatric participants.<sup>31</sup> However, current applications remain limited to research settings, underscoring the need for policy changes to integrate wearables into the safety protocols of youth sports federations.<sup>32</sup> Future development should prioritize affordable, child-appropriate designs to ensure accessibility across socioeconomic groups, as only 4% of existing studies address postoperative monitoring in disadvantaged populations. By combining wearable data with machine learning analytics, clinicians may soon predict injury risks with 76–89% accuracy based on movement patterns, paving the way for truly personalized prevention strategies in pediatric athletics.

### Conclusion

This review highlights the complex landscape of pediatric sports injuries, revealing critical patterns that evolve with athlete development. Younger children face higher fracture risks during informal play, while adolescents demonstrate greater vulnerability to overuse injuries and psychological barriers during recovery. The effectiveness of prevention programs, such as neuromuscular training, highlights the value of structured interventions; yet, significant gaps remain in addressing the risks of sport specialization and the long-term impacts on mental health. Recovery of physical conditions must proceed in concert with psychosocial support, which attempts to counter perceived threats to athletic identity. As coaches notice these signs, clinicians should have the training to ensure that developmental assessments are prioritized when designing care plans. To achieve equitable outcomes, researchers must focus on the longitudinal outcomes and study diverse populations. They are great advocates for balanced participation and providing emotional support during recovery. However, evidence-based medicine and good judgment about the physical, emotional, and socially evolving needs should be integrated through each growth stage and competition to protect young athletes. The future of youth sports safety depends on translating these insights into practical, accessible strategies that can be applied across all levels of participation.

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