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SYSTEMATIC REVIEW

Primary Periphyseal Stress Injuries in Young Athletes: A Systematic Review

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Abstract

Background Overuse injuries are common in sporting children and adolescents. These injuries are a particular concern when they involve the epiphyseal–physeal–metaphyseal (EPM) complex given their potential to disturb skeletal growth. Specifically, the limits of mechanical tolerance of the EPM complex to repetitive stress may be exceeded by the intense and continuous training characteristic of many youth sports today.

Objective This article describes the present status of knowledge on the occurrence and outcome of primary periphyseal stress injuries (PPSIs) affecting the EPM complex in the extremities of children and adolescents involved in youth sports.

Methods A comprehensive review of the sports medicine literature was conducted to determine the nature and extent of PPSIs affecting the EPM complex of the extremities among youth sports participants and the potential for consequent skeletal growth disturbance and resultant limb deformity associated with these injuries.

Results Our initial search uncovered 128 original published scientific articles reporting relevant data on PPSIs. There were 101 case reports/series, 19 cross-sectional, 1 case–control, and 7 cohort studies with relevant data. The case reports/series studies reported 448 patients with PPSIs involving the extremities. Children and adolescents representing a variety of high impact repetitive youth sports activities—including baseball, badminton, climbing, cricket, dance, gymnastics, rugby, soccer, swimming, tennis, and volleyball—may sustain PPSIs involving the shoulder, elbow, hand and wrist, knee, and ankle and foot. Although incidence data from prospective cohort studies are lacking, data arising from cross-sectional studies suggest that PPSIs may be common in select groups of youth athletes—including the shoulder in baseball players (0–36.6%), wrist in gymnasts (10–83%) and platform divers (52.6%), and fingers in rock climbers (5–58%). Notably, not all stress-related skeletal changes detected on imaging were symptomatic in these studies. When diagnosed and treated with an appropriate period of rest and rehabilitation, most patients studied were able to return to their sport activities. However, our data also show that 57/448 PPSIs (12.7%) produced growth disturbance, and that 28/448 patients (6.2%) underwent surgery for their injuries. Absence of treatment, delayed presentation and diagnosis, and non-compliance with a rest regimen were common in cases that produced growth disturbance.

Conclusions PPSIs may affect the extremities of children and adolescents engaged in a variety of youth sports, especially at advanced levels of training and competition. Most skeletally immature patients with PPSIs respond well to timely treatment; however, in extreme cases, PPSIs can progress to produce skeletal growth disruption which may necessitate surgical intervention. Clearly, establishing the early diagnosis of PPSIs and providing timely treatment of these injuries are needed to ensure the skeletal health of youth sports participants. Rigorous prospective longitudinal epidemiological and imaging studies designed to provide incidence rates of PPSIs and to determine the effect of PPSIs on long-term skeletal health are also necessary.

1 Background

Participation in youth sports is increasingly popular for children and adolescents. Trends in youth sports over recent decades include increased duration and intensity of physical loading, earlier specialization and year-round training, and increased difficulty of skills practiced [1]. In addition to traditional sports, children and adolescents are increasingly

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Key Points

Participants in a variety of youth sports and high impact repetitive activities may sustain PPSIs involving the shoulder, elbow, hand and wrist, knee, ankle and foot.

Most PPSIs respond well to timely treatment. However, in the absence of proper treatment, some of these injuries progress to partial or complete premature physeal closure and limb deformity.

Rigorous prospective longitudinal epidemiological and imaging studies of youth sports participants designed to provide incidence rates of PPSI and to determine the effect of PPSIs on skeletal health are necessary.

visiting wilderness recreational destinations and participating in a growing number of adventure and extreme sports [2].

Today, intensive specialized sport training is often initiated at an early age when skeletal growth is still ongoing [3, 4]. It is not uncommon, for example, for children as young as 6–8 years of age to play organized hockey or soccer and travel with select teams to compete in other towns and communities [4]. Similarly, young athletes, ages 12–13 years, may train 15–20 h/week rock climbing or skate-boarding, or at regional training centers in sports such as tennis or gymnastics [4, 5].

Incentive for advanced training and competition for elite youth athletes is provided by international sporting federations [6]. For example, the International Olympic Committee recently introduced Youth Olympic Games for young athletes, ages 14–18, including adventure and extreme sports such as mountain biking and sport climbing [6, 7]. Mass media showcasing these sports are also helping to drive their popularity among youth.

The benefits for youth who engage in regular physical activity and sport include improved bone health, weight status, cardiorespiratory and muscular fitness, cognitive function, and a reduced risk of depression [8]. The potential benefits of ongoing sport participation in youth also include improved self-esteem, motor coordination, and social skills [9]. Nevertheless, year-round participation in youth sports which involves high levels of repetitive training fosters an environment where overuse injuries are likely to occur [10]. This may be especially true at the elite level given the intensive training programs and high-frequency participation in sporting events [4, 5, 11, 12].

Overuse injuries are common in youth sports and can counter the beneficial effects of sports participation at a young age if a child or adolescent is unable to participate because of the residual effects from prior injury [13, 14]. The concern is that the limit for mechanical tolerance of growing bones may be exceeded by the intense and continuous training characteristic of many youth sports today [15]. Overuse injuries of the extremities are a particular concern given the potential for growth disruption and resultant deformity of long bones, especially during periods of rapid growth [10, 15–17]. Since overuse injuries may involve one or more constituents of the epiphyseal–physeal–metaphyseal (EPM) complex [18, 19], it makes sense to collectively refer to these injuries as primary periphyseal stress injuries (PPSIs).

Parents want to know whether a given sport is safe for their children. Indeed, children and adolescents and everyone who works with them, whether they are parents, coaches, or medical personnel—including consultants, general practitioners, junior doctors, and medical students—need to have a better understanding of the extent of PPSI occurrence in youth athletes and the potential for skeletal growth disturbance associated with these injuries. This article describes the present status of knowledge on the occurrence and outcome of PPSIs affecting children and adolescents involved in youth sports.

2 Methods

A systematic review of the literature was performed applying the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines [20] (Fig. 1). The primary reference source for this study was the electronic database SCOPUS, which includes Medline and CINAHL databases. The literature search was limited to published, peer-reviewed reports—including case series and data arising from injury registries (>4 cases), cross-sectional, case–control, and cohort studies—and involved the following search terms as well as extensive cross-referencing: growth plate injury, physeal injury, epiphyseal injury, epiphyseal plate injury, and metaphyseal injury in combination with athletic injuries, youth sports, injury, and injuries. Each title was searched manually for any focus on stress-related injuries involving one or more constituent parts of the EPM complex of the long bones in youth athletes. Only English-language articles published in peer-reviewed journals with an emphasis on human participants were initially included. Titles focusing on sport-related apophyseal injuries and those isolated to the cortex of the metaphysis or diaphysis were excluded. The reference lists of selected articles were manually searched using the same criteria. Based on these search criteria, 2530 articles were identified and 85 additional records were identified through other sources. Using the PRISMA guidelines [20], studies were selected based on appropriateness of topic and full-text options. The literature search was finalized on 10

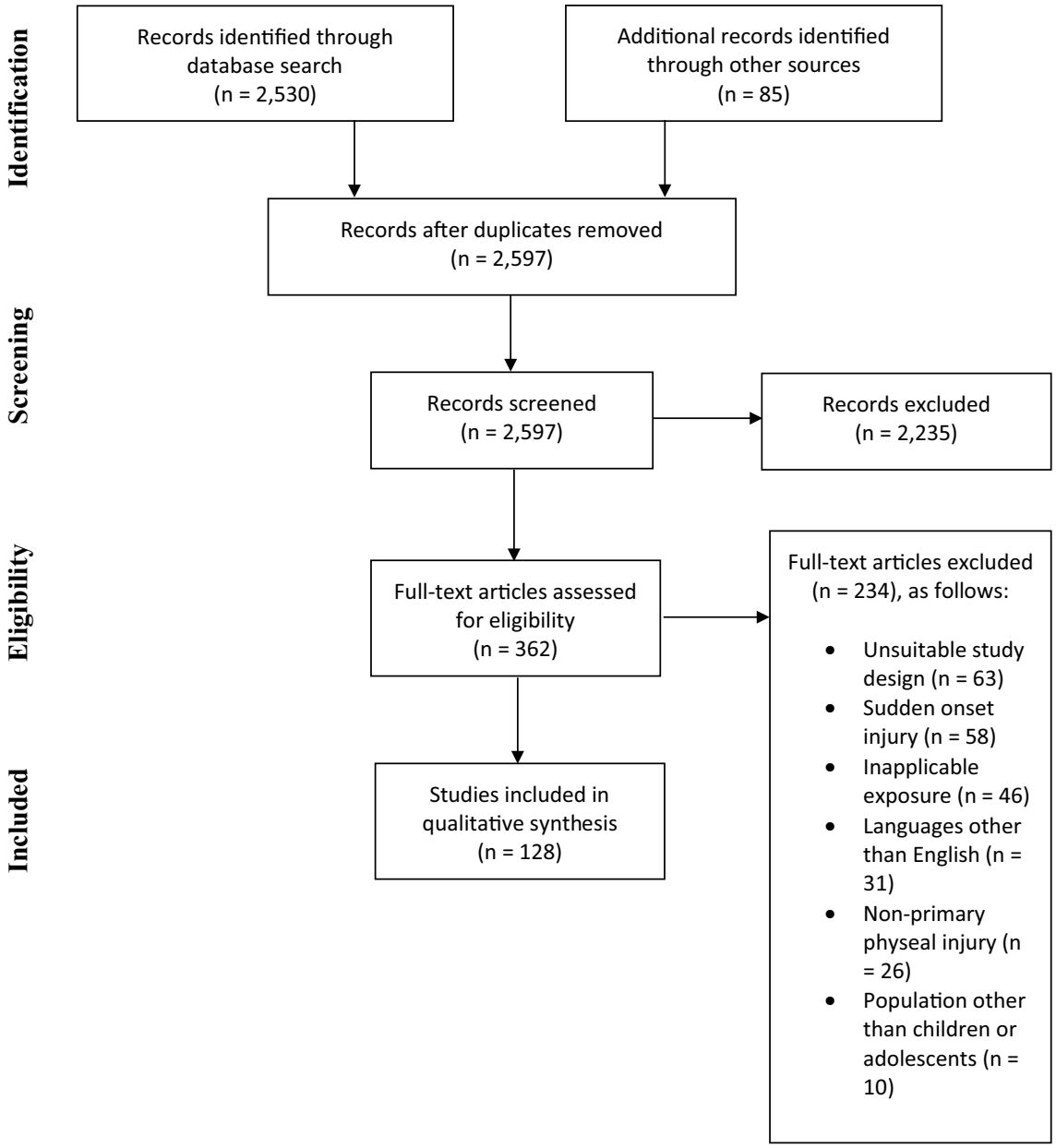

Fig. 1 Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram

January 2021 and yielded 128 articles which included data relevant to the study question (Fig. 1).

3 Results

Of 128 original published scientific articles reporting with relevant data on PPSIs, 101 were case reports and case series involving the upper and lower extremities of youth athletes. Further search uncovered 19 cross-sectional, 1 case–control, and 7 cohort studies with relevant data. Notably, there is a general pattern of increased number of original PPSI reports (case, cross-sectional, cohort) published per decade between 1950 and 2019 (Fig. 2). A description of our study results relative to study design is provided below prefaced by a review of current knowledge regarding the pathomechanism of PPSIs.

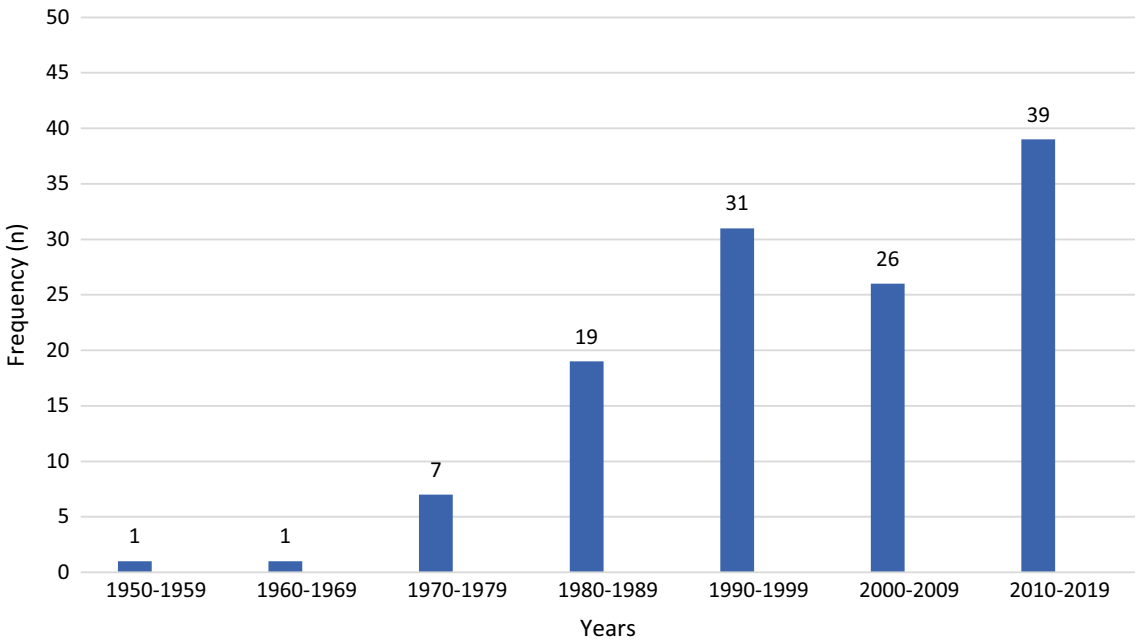

Fig. 2 Primary periphyseal stress injuries (PPSIs): frequency of reports published per decade (1950–2019). 4 articles published in 2020 are not included in this figure

3.1 Pathomechanism

PPSIs can develop following repetitive submaximal stress causing microtrauma to one or more constituents of the EPM complex, particularly at the end of a long bone [21–24]. While the precise nature of chronic microtrauma in these injuries depends on their anatomical location, sport, and offending action, the forces tend to include one or more repetitive compressive, rotational, traction, tension, and/or shearing strains (see Table 1).

The most common radiographic or magnetic resonance imaging (MRI) finding is widening of the physis (Fig. 3) [21]. Initially, this injury was believed to be a stress reaction or stress fracture through the primary physis [25, 26]. In reality, the stress-related epiphyseal plate widening observed on imaging in the pediatric patient begins in the metaphysis with disruption of the normal metaphyseal blood supply [18, 21, 23, 27]. This metaphyseal stress injury is theorized to occur through repetitive loading, which alters metaphyseal perfusion and, in so doing, interferes with the apoptosis of the hypertrophied chondrocytes, which typically occurs in the zone of provisional calcification [18, 21, 22].

The hypertrophic zone and, by extension the physis, continue to widen because of ongoing growth in the germinal and proliferative zones [18]. These insults are reproduced in experimental animal models by the disruption of metaphyseal blood flow [23], and in skeletally immature children who participate in high-level sports and sustain repetitive trauma [27]. The resulting physeal widening, although it may mimic a non-displaced Salter–Harris type I fracture, is not a true fracture [21, 28]. On magnetic resonance imaging (MRI), there is no discontinuity or fluid-like signal intensity cleavage plane through the physeal cartilage to suggest fracture [21, 23].

The widening of the growth plate within the hypertrophic zone is usually reversible once normal metaphyseal perfusion is restored, as the resting and dividing cellular layers of the growth plate, and the attendant epiphyseal and metaphyseal blood supplies, are essentially undisturbed [21]. However, if metaphyseal stress injuries are undiagnosed or sub-optimally treated, progressive mechanical insults may lead to stress fractures involving one or more components of the EPM complex, especially if training is continued [16, 17, 24]. Although these injuries may eventually produce Salter–Harris type fracture patterns [29], their hallmark is a gradual onset of clinical symptoms [15–17].

In some instances, metaphyseal stress injuries and stress fractures involving the EPM complex may involve injury of the epiphysis and adjoining portion of the growth plate, which explains the reported cases of permanent growth arrest and long-term deformity [15–17, 21, 24]. In these injuries, damage to the epiphyseal-sided vessels may harmfully affect the resting or germinal zone of the physis which provides a ready stock of chondrocytes for the physis [28]. This injury may be localized and cause asymmetric growth, or it may involve the entire physis and cause a reduction in

Table 1 Summary of biomechanical forces related to primary periphyseal stress injuries

Anatomical location	Sport/activity	Offending action	Biomechanical forces
Proximal humerus	Badminton, baseball, cricket, gymnastics, swimming, volleyball	Repetitive throwing, repetitive overhead sports	Compression, rotation, and traction
Distal humerus	Baseball, gymnastics	Repetitive throwing, repetitive loading on vault	Compression, rotation
Proximal radius	Gymnastics	Repetitive loading through elbow and wrist	Primarily compression, but can also be rotation (vault), and traction (uneven bars)
Distal radius	Badminton, diving, gymnastics, rock climbing	Repetitive trauma when the wrist is in extension	Compression
Middle finger, middle phalanx	Rock climbing	Crimping position (flexion of the PIP joint) from repetitive loading	Compression, tension
Fourth (ring) finger, middle phalanx	Rock climbing	Crimping position (flexion of the PIP joint) from repetitive loading	Compression, tension
Thumb	Piano player, rock climbing	Repeated contact at the radial aspect of the thumb	Tension, compression, shear forces
Proximal femur	Dance, gymnastics, tennis	High impact, repetitive loading	Compression
Distal femur	Baseball, figure-skating, gymnastics, running during basketball or football training, soccer, softball, tennis	High impact, repetitive loading	Compression, shearing, valgus, or varus forces
Proximal tibia	Baseball, basketball, cheerleading, dance, gymnastics, long-distance running, rugby, soccer, softball, tennis	High impact, repetitive loading	Compression, shearing, valgus, or varus forces
Distal tibia	Basketball, dance, figure-skating, football, soccer	High impact, repetitive loading	Compression, rotation
Second metatarsal	Dance	Asymptomatic repetitive stress from dancing en pointe	Compression, rotation
Great toe (Hallux)	Ballet, basketball, long-distance running	Repetitive loading on the great toe	Compression, rotation

PIP proximal interphalangeal joint

the rate of growth or complete cessation of further growth [21, 24]. In either case, premature closure and deformity of some or all of the physis may occur [21, 24].

3.2 Case Reports/Series

Case reports and case series are numerator-based study designs and therefore cannot be used to generate incidence rates of PPSIs. However, they can provide useful information as to the existence and relative frequency of this condition, preferred or successful treatments, and clinical outcome. They can also provide important insights into injury etiology that are useful for injury prevention work [30]. Case data on PPSIs are discussed below relative to body location.

3.2.1 Shoulder

Baseball pitchers were the first youth athletes in whom a PPSI was reported. An overuse condition that affects the proximal humeral physis of the throwing arm of skeletally immature youth baseball pitchers, "Little Leaguer's Shoulder (LLS)," was first described in 1953 by Dotter [25]. LLS is believed to stem from chronic repetitive micro-traumatic shear, torque, or traction forces imposed on the unossified cartilage of the proximal humeral physis [31]. Classic radiographic findings of LLS can include physeal widening of the proximal humeral physis, sclerosis of the proximal humeral metaphysis, and fragmentation of the lateral aspect of the proximal humeral metaphysis [32] (Fig. 4).

Overall, there were 33 case reports and series describing 197 cases of LLS in youth athletes, ages 10–19 years

Fig. 3 15-year-7-month-old boy who is a football place kicker. Reproduced from Laor et al. [21], with permission. **A** Frontal radiograph of right knee shows broad band of physeal widening of lateral aspect of distal femoral physis (arrow). **B** Corresponding coronal fast spin-echo proton density-weighted image with fat saturation shows broad area of lateral physeal widening of distal femur (arrow). Signal is isointense to that of rest of physis. **C** Frontal radiograph obtained 3 months after immobilization shows near-complete normalization of physeal widening

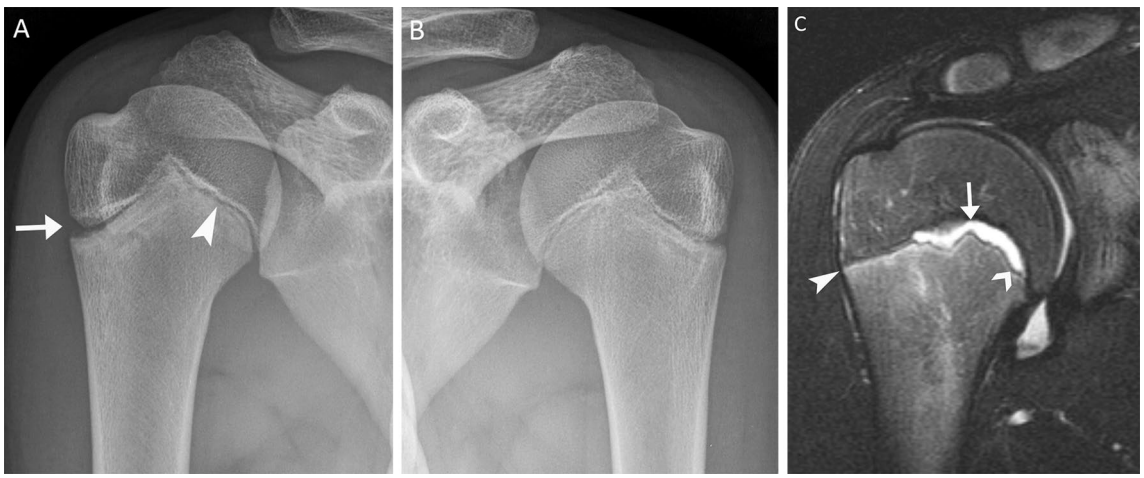

Fig. 4 Little Leaguer's shoulder. **A**, **B** Frontal radiograph of the symptomatic right shoulder from a 13-year-old boy who is a baseball pitcher and with 3 months of symptoms shows asymmetric widening (arrow) of the lateral portion of proximal humeral physis when compared to the normal medial portion (arrowhead). Note the subtle subjacent metaphyseal sclerosis of the right shoulder, which is asymmetric when compared to the asymptomatic left shoulder (**B**). **C** Oblique coronal T2-weighted image from a 15-year-old boy who is also a baseball pitcher and with acute on chronic symptoms shows focal physeal widening centrally (arrow) when compared to the more normal appearance of the peripheral physis (arrowhead). Note the reconstituted zone of provisional calcification (chevron) that reflects healing changes in response to conservative treatment (cessation of overhead throwing)

[25, 31–61]. While most commonly reported in male baseball pitchers, LLS also occurs in females [31, 57, 60, 61] and other baseball positions [31, 40, 45, 51, 53]. These injuries have also been reported in other overhead sports including badminton [54], cricket [56], football [48], gymnastics [57–59], tennis [31, 46], swimming, and volleyball [60, 61]. There is also a reported case of bilateral physeal stress lesions of the proximal clavicular physis in a skeletally immature male gymnast [62].

Notably, a case series study at a high-volume regional children's hospital reported an annual increase in the number of patients diagnosed with LLS over a 14-year period [31], with a significant increasing trend in the presentation of patients diagnosed with LLS during 1999–2013 ($P = 0.02$). Specifically, the incidence of LLS, a reflection of the volume of LLS relative to overall departmental and divisional patient volume, increased approximately 8% per year on average (annual percentage change = 8.5; 95% CI 5.5–11.6) [31].

In the studies reviewed, treatment of LLS was conservative in all but one subject [37] who underwent an arthroscopic procedure to remove loose bodies related to avascular necrosis of the proximal humerus. Treatment generally involved rest from the exacerbating activity, including time off from the sport followed by a gradual return to activity. Several studies reported that injured players were encouraged not to pitch again until their physes have closed [33, 34, 56]. Physical therapy was prescribed to improve strength and throwing mechanics in some patients [2, 47, 49, 50, 53, 58]. The recommended length of rest typically varied from 6 weeks to 3 months, with full resolution of symptoms ranging from 6 weeks to 12 months. In several cases, the patient returned to a different position or sport [37, 43, 56]. Notably, a report of 95 patients with LLS found that the average time to full resolution of symptoms was 2.6 months, with an average time to return to competition of 4.2 months [31].

3.2.2 Elbow

Eight studies reported 22 PPSIs of the distal humerus and proximal radius involving 6 males, 10 females, and 6 males or females, ages 7–18 years [63–70]. Six of the eight studies [65–70] reported on injured gymnasts, whereas two studies [63, 64] involved baseball players.

PPSIs involving the longitudinal growth centers of the elbow were first reported in 1975 by Ellman [63] who documented angulation deformity of the radial head in four male baseball players. This injury was believed to reflect underlying growth disturbance involving the growth plate of the head of the radius which occurred following lateral compression forces arising from repetitive baseball throwing [63].

PPSIs involving the proximal radius have also been reported in 21 male and 21 female artistic gymnasts [65–70]. In gymnastics, full extension loading exercises cause maximal compressive forces to be transmitted through the lateral aspect of the radial head which can lead to depression and eventually partial growth arrest and stress fracture (Salter–Harris type IV/V) of the antero-lateral aspects of the proximal radius [66, 70].

Injury to the distal humerus of a skeletally immature baseball player was first reported by Podestra et al. [64] who treated a 7-year-old baseball player with distal humeral epiphyseal separation from excessive repetitive throwing. Oda et al. [68] reported an 11-year-old male gymnast with chronic slipping of the distal humeral epiphyses bilaterally. In this patient, it was believed that the repetitive biomechanical loading on the elbows during the vault induced injury to the growth plate bilaterally, with chronic progression to separation of the distal humeral epiphyses [68].

Conservative management was provided in 12 of 22 patients with elbow PPSIs that involved rest with or without long-arm casting, upper extremity weight-bearing restrictions, and physical therapy, with gradual return to former levels of activity in 6–12 weeks [63–70]. Ten patients underwent surgery including arthrotomy [63], reduction and internal fixation of the growth plate [63, 65, 69, 70], tension band wiring [68], excision of the radial head [63, 66], and proximal radial osteotomy [63]. Although 7 studies reported follow-up of injured athletes [63–65, 67–70], only 4 studies reported return to activity data, which ranged from 8 weeks to 8 months [64, 67, 69, 70]. Three studies reported 7 injured athletes withdrew from gymnasts pursuant to injury [65, 66, 70].

Five studies reported postsurgical follow-up time, which ranged from 0 to 120 months [63, 65, 68–70]. However, return to activity data for surgically managed athletes was sparse. Only 3 studies indicated whether the gymnasts actually returned to their sport [65, 69, 70]. In these studies, 4 patients continued with gymnastics [65, 69] and 3 retired from gymnastics [65, 70].

3.2.3 Wrist

Overall, there were 28 case reports and series describing 98 patients with PPSIs involving the distal radius and, infrequently, the ulna in young athletes, ages 10–22 years [71–97]. Both female ($n = 65$) and male ($n = 33$) athletes were involved. With the exception of three cases—in badminton, climbing, and break dancing [71–73]—the PPSIs involved the distal radius of female and male gymnasts [74–97]. This is perhaps not surprising given the repetitive compressive and rotational forces on the forearm in this sport and the greater cross-sectional area of the distal radius compared to the distal ulna. In the neutral position with neutral ulnar variance, 80% of axial loads are borne by the radius and 20% by the ulna [96]. In children and adolescents, the ulna tends to be relatively shorter than the radius at the carpus (i.e., ulnar-negative), which drastically increases the load on the distal radius [95]. In gymnasts, the result is disproportionate loading of the epiphysis and primary physis of the distal radius [19, 81].

Stress injuries affecting the distal radius of gymnasts were first reported in 1981 by Read [74] who treated stress fractures of the epiphysis and metaphysis in the distal radius of three female gymnasts, ages 12–16. In 1985, Roy et al. [26] described a stress reaction involving the distal radial growth plate in a series of male and female gymnasts, ages 10–17. Radiographic criteria included: widening of the growth plate, cystic changes of the metaphyseal aspect along the growth plate, a beaked distal volar and radial aspect of the physis, and haziness within the usually radiolucent area of the growth plate (Fig. 5) [26]. Following the early studies by Read [74] and Roy et al. [26], multiple case reports/case series studied this injury in young female and male gymnasts [75–97]. PPSIs of the distal radius in gymnasts are often referred to as "Gymnast wrist" [84, 87, 88, 96–98].

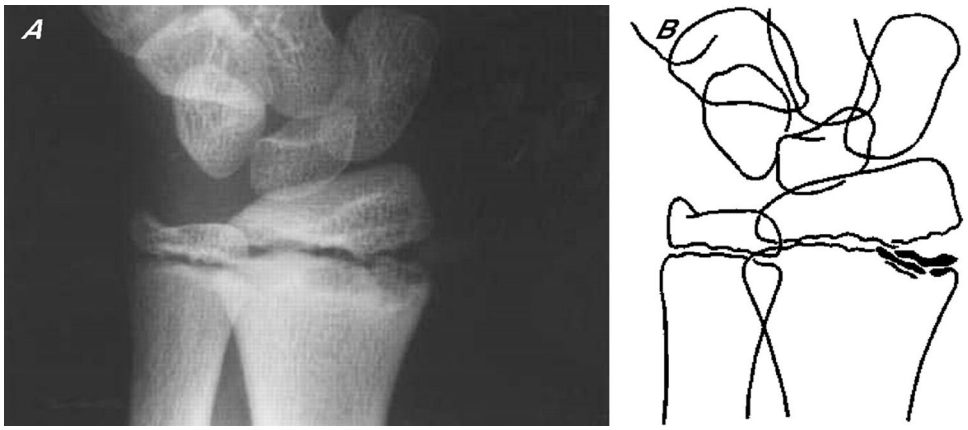

Fig. 5 Gymnast wrist. **A** Radiograph and **B** line drawing of the wrist in a symptomatic female gymnast with findings of widening of the distal radial physis, and cystic changes and irregularity of the metaphyseal margin. Reproduced from Roy et al. [26], with permission

Management of wrist PPSIs has typically been conservative, involving rest from the exacerbating activity until resolution of symptoms and radiographic evidence of healing. Treatments prescribed to stabilize or otherwise immobilize the wrist joint included wrist taping [93], bracing [72, 94], splinting [85, 89], and use of a cast (e.g., short-spica cast, short arm cast, and palm-to-elbow cast) [71, 73, 75, 79, 82]. The rehabilitation programs employed in some patients aimed to improve strength and mobility [26, 76, 89]. Following appropriate rest and rehabilitation, the vast majority of patients were able to return to their sport. Time to recovery was reported in some studies and ranged from 1 week to 12 months [26, 71–77, 79, 82, 85, 87]. Several studies [74, 84, 87, 92] reported patients ($n = 8$) who dropped out of gymnastics pursuant to PPSI of the distal radius.

Surgery was performed on nine gymnasts and involved removal of loose bodies from the wrist in one patient [76], arthroscopic procedures with debridement of the torn portion of the triangular fibrocartilage complex (TFCC) in 1 patient [87], ulnar arthroplasty in 2 patients [80, 84], distal ulnar recession in 2 patients [84], and ulna shortening osteotomy in 3 patients [81, 87, 92]. Postoperatively, 5 of 9 gymnasts were able to return to full gymnastics activity within 4 weeks to 15 months. [76, 81, 84, 87]. Return to activity information was not provided for 3 patients [76, 80, 87], including one report which noted that the ulna shortening osteotomy was unsuccessful [87].

3.2.4 Hand/Fingers

Overall, there were 11 case reports and series describing 80 patients, including 65 males and 15 females, ages 11–17, with PPSIs involving the hand and fingers [16, 17, 72, 95, 99–105]. With the exception of 2 patients, both gymnasts [95], the remaining PPSIs involved the fingers of rock climbers. There was also one case of physeal growth arrest of the distal phalanx of the thumb in a skeletally immature pianist, presumably caused by accumulated repetitive trauma incurred during years of piano playing [106].

In addition to their observation of PPSIs involving the distal radius of skeletally immature female gymnasts, Dwek et al. [95] observed osseous abnormalities of the metacarpal heads in two gymnasts, including flattening and irregularities of the overlying articular surface. Dwek et al. [95] suggested that these findings were typical of avascular necrosis of the metacarpal head, likely from chronic impaction across the metacarpophalangeal joints during gymnastics [95].

Among reports of injuries involving climbers, the most frequent PPSI reported was a stress-related Salter–Harris type III fracture at the dorsal aspect of the middle phalanx, with injury to the middle finger being most common followed by the ring finger [16, 17, 101, 104, 105]. This injury distribution is supported by a biomechanical analysis during climbing, which reveals that the most significant fingertip forces are applied by the middle finger [107, 108].

Epiphyseal stress fracture of the finger phalanges among sport climbers is a climbing-specific injury which was first described by Hochholzer et al. [99] and Chell et al. [100]. Since then, there have been multiple case reports/series studies of this injury [16, 17, 72, 99–105]. PPSI may be a common injury in youth climbers who have finger pain. In one study, 14 of 20 youth (≥ 14 years of age) who presented with symptoms related to climbing showed an epiphyseal fatigue fracture on MRI, including one with bilateral injury [102].

One possible mechanism for epiphyseal fractures in the phalanges of young climbers could be the development of chronic microfractures on the dorsal epiphysis, because when the finger is flexed during climbing, particularly during crimping, maximum pressure is placed on the base of the middle phalanx [17]. During crimping, there is a translation of the base of the middle phalanx in relation to the head of the proximal phalanx [16]. This translation decreases the joint's congruence and joint contact area and shifts the point

of maximum pressure more dorsally, leading to an increased risk of PPSI [16, 109].

Treatment of the fingers was almost always conservative if the fracture was not widely displaced [16, 17, 101–103, 106, 107]. Most authors recommended an early functional treatment without immobilization for about 6–8 weeks [16, 17, 101, 104, 107]. Patients used their hands for daily living activities but refrained from any hand-related sport (not only climbing but also gymnastics, handball, volleyball, etc.) and manual work/labor. Two studies reported the use of finger splints for 2–3 weeks with good results [17, 72]. After clinical and radiographic/ultrasound assessment, gradual restart of sport-specific activities resumed after 8–12 weeks with good results [16, 17, 99, 101, 102, 105, 107]. Notably, patients experienced better results if treatment, including cessation of activity, began immediately after the onset of symptoms [16, 17].

Surgical treatment for repetitive stress-related fracture nonunion was performed in two climbers using a spot drilling epiphysiodesis technique. Both patients went on to fracture union after surgery, without complications, and returned to sport climbing within 3 months of treatment [104].

3.2.5 Knee

Overall, there were 13 case reports/series describing 26 patients, including 17 males and 9 females, ages 8–15, with PPSIs involving the distal femur, proximal tibia, or proximal fibula [21, 88, 110–121]. These injuries are believed to result from repeated compression, rotational, shearing, valgus, or varus forces on the knee ensuing from repetitive trauma during sports activities [110, 118, 120, 121]. Patients represented a wide range of youth sports including baseball [88], basketball [21, 110, 111], football [21], gymnastics [11, 21, 113], rugby [118], softball, running [119], soccer [21, 120], tennis [21, 121], as well as engagement in multiple sports [114–116]. There was also a report of one patient who participated in recreational sports only [117].

In most instances, imaging of knee PPSIs revealed metaphyseal stress injury of the distal femur and/or proximal tibia, including physeal widening and metaphyseal irregularities [21, 112–115, 117–119, 121] (Fig. 3). One study reported four patients—a gymnast, soccer player, and two multisport athletes—with stress injury of the proximal tibial epiphysis [116].

Management was generally conservative, and involved strict rest from the exacerbating activity with/without immobilization followed by gradual return to activity [21, 112, 116, 119, 121]. In some patients, restriction of movement was facilitated with the use of crutches [114], knee immobilizers [21, 112], or a long leg cast [21]. The duration of rest and gradual return to sport ranged from 4 to 20 weeks depending on the severity of the injury. One patient, who was noncompliant, developed varus deformity of the knees and had persistent knee pain at 4 year follow-up [21].

Surgery was performed in 7 patients [110, 111, 118, 120], which included exploratory surgery for premature closure of the lateral aspect of the right proximal tibial growth plate [110], correction of recurvatum, and valgus alignment of the knee arising from asymmetric premature closure of the proximal tibial growth plate [111], varus opening wedge osteotomy to restore the alignment of the proximal tibia [118], hemiepiphysiodesis with insertion of a medial tension band plate for guided growth and gradual correction of the deformity, and lateral distal femoral opening wedge osteotomy [120]. Length of patient follow-up ranged from 5 to 24 months during which time patients were able to return to their sporting activity [110, 118, 120]. One study reported excellent results 2 years post-surgery but did not indicate whether the 2 patients were able to return to their sport [111].

3.2.6 Ankle/Foot

Overall, 8 studies reported 25 PPSIs of the ankle and foot affecting youth athletes, ages 9–16 (2 males, 5 females, 18 M/F), involved in basketball [122], dance [123–126], dance/gymnastics [124], distance running [128], soccer [129], as well as those involved in multiple team sports [127].

Stress changes of the distal tibial physis were reported in a recreational dancer/gymnast [124] and in the distal tibia and/or fibula of 18 patients active in team sports such as soccer, basketball, and football [127].

Other PPSIs involved the feet and include the proximal first metatarsal in a basketball player, distance runner, and soccer player [122, 128, 129], second metatarsal in two dancers [123, 126], and a non-healing stress fracture of the proximal phalanges of the great toes in a ballet dancer [125].

Treatment was generally conservative and involved restriction of weight-bearing and gradual return to activity [122–124, 127, 128]. For some patients, treatment included shoe modification [122, 126], use of crutches [123], ankle cast followed by walking boot [124] ankle bracing [127], and physical therapy [129].

In one study [124], two dancers were able to return to activity without restrictions after 6 months, while in a second study, the dancer was not able to return to dancing until 13 months, but at a lower intensity [123].

Only one patient underwent surgery [125]. A ballet dancer underwent a closed reduction and Herbert screw insertion which was performed bilaterally to manage non-healing stress-induced fractures of the proximal phalanges of the great toes [125]. After 6 months, significant resolution of the symptoms and complete radiological union occurred, allowing a return to ballet training [125].

3.2.7 Bone Growth Disturbance

In the case reports/case series studies reviewed, there were 448 patients with PPSIs affecting the shoulder, elbow, wrist, hand/fingers, knee, and ankle and foot. Among these reports, there were 57 patients (12.7%) with radiographic evidence of bone growth disturbance involving the shoulder, elbow, wrist, hand and fingers, knee, foot and ankle [16, 17, 21, 40, 51, 58, 63, 65, 66, 70, 75, 80, 81, 84, 86, 87, 90, 92–94, 106, 110, 111, 118, 120, 123, 126] (Table 2). In these patients, the severity of the injury likely resulted from the absence of treatment, or delay in treatment, and/or non-compliance with treatment recommendations [21, 81, 102, 107].

Patients exhibiting PPSI growth-related complications represented a variety of sports including baseball [40, 51, 63], basketball [21, 110, 111], climbing [16, 17], dance [123, 126], football [21, 120], gymnastics [21, 58, 65, 66, 70, 75, 80, 81, 84, 86, 87, 90, 92–94], rugby [118], soccer [21, 120], and tennis [21] (Table 2).

Radiographic and/or MRI evidence of growth complications involving the proximal humerus includes varus and extension deformation [51] in a young baseball player and premature closure of the proximal humeral epiphysis in a baseball player and gymnast [58].

Radiographic and/or MRI evidence of growth complications following stress-related injury include flattening and anterior depression of the radial head epiphysis in baseball players [63] and gymnasts [65, 66, 70]. This growth disturbance likely occurred following physeal compression stresses, resulting in damage to the epiphyseal plate and subsequent angulation deformity [63, 66].

Numerous case reports provide radiographic and/or MRI evidence of growth disturbance at the distal radius [75, 80, 81, 84, 86, 87, 90, 92–94]. Chronic, untreated PPSI of the distal radius can lead to premature closure of the physis, resulting in growth arrest (Fig. 6). Serial radiographs show stress-related changes of the distal radial growth plate of the involved extremity, followed by the development of positive ulnar variance due to blunted growth or premature closure of the distal radial growth plate before that of the ulna [19, 92, 130, 131].

A Madelung or Madelung-like deformity (premature closure of the ulnar aspect of the distal radial growth plate) was described in three female gymnasts [80, 87, 93, 94]. Evidence of palmar and ulnar tilting of the distal radial articular surface, a mild form of Madelung-type deformity, has also been reported in several cases of skeletally immature gymnasts with PPSIs [26, 76, 81]. In one case involving a skeletally immature gymnast, radiographs showed widening of the radial aspect and premature closure of the ulnar aspect of the distal radial physis [90].

There are several instances of premature closure of the physis or deformities as a consequence of PPSIs that did not heal among skeletally immature climbers (Fig. 7) [16, 17]. In non-healing injuries, surgical spot drilling epiphysiodesis was performed [105]. The only other case report of growth disturbance in the finger, presumably as a consequence of repetitive loading, is in a piano player [106]. In this instance, it is likely that repeated contact at the radial aspect of the thumb results in tension and compression [106].

There is radiographic and MRI evidence of stress-related growth disturbance, including secondary valgus and varus deformity involving the proximal tibia [21, 110, 111, 118] and distal femur [21, 120] in youth basketball, football, gymnastics, rugby, soccer, and tennis. The proximal tibia and distal femur contribute 55–70% to the growth of their respective bone, and thus, growth disturbance at these locations could result in substantial limb shortening or deformity [18, 21].

Radiographic and MRI evidence of PPSI-related bone growth disturbance in the feet has been reported in two female dancers [123, 126]. In a skeletally immature Flamenco dancer [123], serial radiographs over 13 months revealed premature closure and shortening of the second metatarsal. In the second dancer, radiographs and MRI revealed a shortened second metatarsal and premature growth plate closure. This growth disturbance likely occurred as a result of repetitive stress from dancing en pointe [126], whereas in the former patient, the premature closure likely resulted from repetitive vibratory stress, as the highest footplate pressures in Flamenco dance are exerted on the first and second metatarsal heads [132].

Information on treatment was unavailable for 5/57 patients who presented with bone growth disturbance, including 4 who dropped out [86, 87]. Treatment was conservative in 33 of 52 patients and involved rest from the offending activities and gradual return to activity. This was accomplished with the use of bracing [94], taping, [94], splinting [17], casting [21], crutches [120], knee immobilizers [21], physical rehabilitation [58], and pain-reducing modalities [93, 94].

Corrective surgery was performed in 19 patients [63, 65, 66, 81, 84, 92, 93, 110, 111, 118, 120]. Most patients were able to return to their sport within 2–36 months of surgery [81, 84, 87, 90, 110, 111, 118, 120]. Several athletes choose to retire after surgery or otherwise participate at a less competitive level [65, 70, 92]. Information on return to activity was not provided for several patients who underwent surgery [63, 66, 75, 80].

3.3 Cross-Sectional Studies

Table 3 summarizes the results of 19 imaging studies which provide prevalence estimates or comparative data on PPSIs involving the shoulder, wrist and fingers of baseball players [133–135], divers [136], gymnasts [26, 27, 137–146], and climbers [147–151]. Cross-sectional data are also provided

Table 2 Case studies reporting primary periphyseal stress injuries associated with growth disturbance and deformity

Sport/study	No. of Subjects	Mean age/age range	Activity	Imaging findings (X-ray, MRI)	Diagnosis	Treatment
Shoulder						
Carson and Gasser 1998 [40]	1 M Baseball	11	A pitcher who had symptoms for 18 months. His chief complaint was pain of the proximal humerus during throwing	By age 15, radiographs revealed premature humeral physeal closure. There was no limb-length discrepancy	LLS	Conservative with rest from throwing and gradual return to throwing. At age 15, he had been throwing asymptomatically for 2 years
Ejnisman et al. 2007 [58]	1 M Gymnastics	15	A national-level gymnast complained of right shoulder pain of insidious onset for 3 months, with no history of acute trauma The pain eventually precluded him from training	Radiographs showed premature closure of the right proximal humeral epiphysis with subtle varus angle deformity	LLS	The patient underwent conservative therapy and refrained from practicing sports for 3 months. Thereafter, a rehabilitation program was established. The patient returned to full training without symptoms 2 months later
Hosokawa et al. 2017 [51]	1 M Baseball	13	Vigorous throwing associated with pitching	Radiographs revealed widening of the proximal humerus physis at age 13. By age 15, CT demonstrated that LLS had acquired varus alignment and extension deformation of the proximal humerus	LLS	Two months of rest from baseball resolved symptoms. Patient successfully returned to his previous level of baseball but retired from this sport at age 15
Elbow						
Ellman 1975 [63]	4 M Baseball	10–12, 17	All patients had experienced gradual onset of swelling and pain in the throwing arm while playing Little League baseball	Radiographs revealed angular deformity of the radial head, with or without associated capitellar osteochondritis and loose body formation	The angulation deformity of the radial head in these patients was believed to be secondary to epiphyseal plate injury caused by lateral compression stress from repetitive trauma	Only one patient was treated conservatively and had a palpable prominent deformity of the radial head at 1-year follow-up. One patient had an arthrotomy to remove loose bodies, one had an excision of the radial head, and another had a proximal radial osteotomy. Residual deformity and impairment in all cases. No data on return to activity

Table 2 (continued)

Sport/study	No. of Subjects	Mean age/age range	Activity	Imaging findings (X-ray, MRI)	Diagnosis	Treatment
Chan et al. 1991 [65]	3 M/F Gymnastics	13.5	All gymnasts trained between 4.5 and 10 h per week	Radiographs showed flattening and anterior depression of the radial head epiphysis in 3 patients which, in one patient who continued training, developed into a chronic Salter type IV stress fracture	Lateral compression injuries of the elbow caused by the forced impaction of the radial head into the capitellum. Salter–Harris fracture (type 4) in one patient, likely caused by repetitive trauma	Surgery: two patients eventually required internal fixation of the growth plate to relieve persistent symptoms. Length of follow-up was 0–120 months. Almost all of the patients were unable to continue gymnastics training
Maffulli et al. 1992 [66]	3 M/F Gymnastics	11–18 M:15.2 F: 11.8	The patients were club (training 2–3 times per week, 90 min per session) to international level (training a minimum of 5 times per week, 120 min per session) artistic gymnasts. All complained of diffuse, dull elbow pain and joint stiffness	Radiographs showed a flattened radial head in three patients (4 elbows); anterior inclination of the radial head (1 elbow)	Deformities may have arisen from compression injury of the subchondral bone with subsequent reshaping of the epiphysis. It is possible that a partial growth arrest (a type V SH injury) may have taken place at the proximal radial physis, inducing inclination deformity	Not reported
Santelli et al. 2019 [70]	3 F Gymnastics	11–12	All presented with a 3 week to 4- month history of unilateral or bilateral elbow pain In one patient, the pain began after a back handspring and persisted with similar activities. In the second patient, the pain started when she switched gyms and significantly increased her hours of training. The third patient described elbow pain which reoccurred with full extension	MRI at 6 months showed bone marrow edema surrounding an intra-articular fracture with anterior deformity of the radial head	Unilateral stress-related Salter–Harris IV fractures of the antero-lateral aspect of the proximal radial head. In one patient, injury proceeded anterior deformity of the radial head	All gymnasts were treated with a long-arm cast for 2–6 weeks. One patient eventually required open reduction and internal fixation of the radial head. Although pain-free with activities of daily living, she retired from gymnastics. The other two gymnasts were able to return to the previous level of gymnastics training after five and eight months, respectively

Table 2 (continued)

Sport/study	No. of Subjects	Mean age/age range	Activity	Imaging findings (X-ray, MRI)	Diagnosis	Treatment
Wrist						
Fliegel 1986 [75]	1 F 1 M Gymnastics	12 14	Competitive gymnasts reported painful swelling of one or both wrists in the absence of a traumatic event. One reported a history of pain over 2 years	Radiographs demonstrated widening of the distal radial growth plate bilaterally	Stress-induced widening of the distal radial growth plate. In the female patient, follow-up after 2 years revealed healing lesions with residual deformity of both distal radii and relative shortening when compared to the ulnae	The female gymnast was advised to discontinue training for 6 months. The left forearm was immobilized in a plaster cast. Clinical symptoms subsided within a year In the male gymnast abstention from gymnastics activities for 6 months resulted in complete healing of the lesion within 9 months
Vender and Watson 1988 [80]	1 F Gymnastics	17	The patient had a 3- to-5-year history of pain on the ulnar side of the left wrist. The pain was increased by an injury that occurred 3 weeks before the examination. She had been training up to 25 h/week for 5 years	Radiographs of both wrists showed an increased ulnar slope of the distal radius articular surface and ulnar positive variance	Premature bilateral closure of the ulnar side of the distal radial growth plate leading to a Madelung-like deformity	Her symptomatic left distal radioulnar joint incongruency was treated with a matched ulna arthroplasty. Return to activity data were not provided
Albanese et al. 1989 [81]	3 F Gymnastics	13.3 12–14 years	Several weeks to 10-month history of wrist pain with participation in competitive gymnastics. Two of the girls trained a minimum of 16–17 h/week	Radiographs showed premature closure of the growth plates of the right distal radius and ulna, with shortening of the radius and alterations in the normal distal radioulnar articulation	Chronic overuse with premature growth plate closure with deformity	In one patient, activity restriction was recommended, but not followed. The second patient was lost to follow-up and returned at age 17 with unresolved wrist pain. The third patient underwent an ulna shortening osteotomy and was able to return to gymnastics
Tolat et al. 1992 [84]	5 F Gymnastics	13–19	Gymnasts at various competitive levels, with wrist pain from two months to two years	Radiographs revealed a positive ulnar variance, ranging from 2 to 11 mm, and disturbance of the distal radial physis	Symptomatic acquired positive ulnar variance from premature closure of the distal radial growth plate	In three cases, surgery was performed (distal ulnar recession in two cases) and patients were able to return to gymnastics with reduced symptoms. Two patients chose conservative treatment, and withdrew from gymnastics

Table 2 (continued)

Sport/study	No. of Subjects	Mean age/age range	Activity	Imaging findings (X-ray, MRI)	Diagnosis	Treatment
Nattiv and Mandelbaum 1993 [86]	1 F Gymnastics	13	Not provided	Radiographs revealed a disturbance of the distal radial physis	Repetitive injury to the distal radial physis leading to hindered radial growth	Not provided
De Smet et al. 1993 [87]	6 F Gymnastics	16–22	Competitive gymnasts who trained 10 or more hours per week with ulnar-sided wrist pain. The pain caused them to stop their training	Radiographs showed that the distal ulna was prominent in all cases, with positive ulnar variance (+2 to + 5 mm)	Stress-related premature closure of the distal radial growth plate with Madelung-type deformity and ulnar wrist pain	4 patients dropped out of gymnastics. One patient underwent an arthroscopic procedure with debridement of a torn triangular cartilage complex and continued her training after two months. One gymnast had a shortening osteotomy of both radii without success
Bak and Boeckstyns 1997 [90]	1 F Gymnastics	14	Gymnast was referred to surgery because of persistent chronic wrist pain associated with gymnastics training	Radiographs showed an open radiovolar aspect of the distal radial physis, whereas the ulna portion showed premature closure	Stress-related premature closure of the ulnar portion of the distal radius physis	To prevent ulnar overgrowth, epiphysiodesis of the distal radius and distal ulna was performed. The patient resumed gymnastics activity at 3 months with partial restrictions and then unrestricted activity at 6 months
Howe et al. 1997 [92]	1 F Gymnastics	14	Competitive gymnast with a 3-month history of chronic right wrist pain	Radiographs showed subtle signs of radial-sided premature physis closure, a possible fracture through the radial epiphysis, and slight ulnar variance. A bone scan showed decreased uptake in the right radius distal growth plate. Repeat radiographs showed complete closure of the right distal radial physis	Premature partial closure of the right distal radial physis	Surgery to shorten right ulna with plate fixation with excellent healing; however, inability to bear weight on right wrist without pain precluded return to gymnastics

Table 2 (continued)

Sport/study	No. of Subjects	Mean age/age range	Activity	Imaging findings (X-ray, MRI)	Diagnosis	Treatment
Brooks 2001 [93]	1 F Gymnastics	21	Collegiate gymnast with no history of wrist injury or pain despite 17 years of competitive gymnastics. She had experienced painful instability and ''giving way'' in her left, non-dominant wrist while practicing an uneven parallel bar routine	Radiographs revealed a Madelung deformity with a widened distal radioulnar joint	Traumatic physeal arrest resulting in Madelung deformity; congenital anatomic variant	Symptomatic treatment and non-steroidal anti-inflammatory medications for pain. Continue to participate successfully in competitive gymnastics, minimally restricted, using palmar wrist tape and a commercially available wrist brace to prevent end-range wrist extension
Barkdull and Annunziata 2007 [94]	1 F Gymnastics	16	Competitive gymnast with persistent right wrist pain for about 4 months. Pain was progressive and had made activities increasingly difficult, especially with those requiring dorsiflexion of the wrist	Mild positive ulnar variance. Radiographs showed partial physeal closure of the ulnar side of the radius with slight ulnar deviation of the epiphysis. MRI showed ulnar positive variance with possible premature closure of the radius	Mild acquired Madelung-type deformity	Patient was urged to discontinue gymnastics. If she desired to continue gymnastics, she could attempt wrist bracing and taping to limit excessive dorsiflexion
Hand/fingers						
Hochholzer and Schöffl 2005 [17]	7 M Climbing (mostly indoor)	14.5 (13–16)	Patients experienced slow onset of pain in PIP joint of the index, long, and ring fingers with no history of acute trauma	Radiographs show epiphyseal fractures of the dorsal base of the middle phalanx. Follow-up showed moderate incongruence of the dorsal base of the middle phalanx (a pre-arthritic deformity) in 5 patients with a longer history of symptoms before therapy. Two patients who disregarded recommendations for rest had poor outcomes and developed partial necrosis of the epiphysis and angular deformity	All patients had a Salter–Harris III injury. These fractures are considered as fatigue fractures caused by repetitive stress and microtrauma	Treatment was conservative: patients with a history of symptoms < 4 weeks received functional therapy and a break of 4 to 6 months. Patients with a longer history of symptoms (> 4 weeks) received functional therapy (e.g., finger gymnastics, ice therapy, non-steroidal anti-inflammatory drugs, and a sport break of 4–6 months) Outcome: minor incongruence ($n = 3$), incongruence ($n = 2$), deformation ($n = 2$)

Table 2 (continued)

Sport/study	No. of Subjects	Mean age/age range	Activity	Imaging findings (X-ray, MRI)	Diagnosis	Treatment
Schöffl and Schöffl 2015 [16]	1 M Climbing (mostly indoor)	14.1	He reported using the crimp grip and performing a hard bouldering move with a sudden onset of pain on one hand, while on the other hand, the pain developed gradually, over time	Radiographs and MRIs revealed epiphyseal stress injury to the PIP joint in the long fingers of both hands	Patient had a crush injury (Salter–Harris V) in both long fingers resulting in growth disturbance and movement impairment	Persisting extension deficit of the PIP joint of 3 degrees for one hand and 5 degrees for the other hand, with dorsal swelling at the PIP joint, but no pain
Attkiss and Bunckle 1998 [106]	1 M Non-athletic	13	The patient presented 3 months after noticing that the distal portion of his non-dominant right thumb was shorter than his left. He denied any history of trauma other than repetitive use of the thumb during piano playing. He averaged 10–15 h per week of practice and reported intermittent pain	On radiographs, the growth plate of the distal phalanx of the right thumb was completely closed. Comparison with left thumb showed relative shortening of the distal phalanx of the right thumb	Physeal growth arrest of the distal phalanx of the thumb presumably caused by accumulated repetitive trauma incurred during years of piano playing	Conservative treatment. Fortunately for this patient, growth arrest occurred relatively late and will result in minimal functional impairment
Knee						
Sato et al. 2002 [110]	1 F Basketball	13	Patient played basketball since age 8. There was slight pain in the right knee which increased over time	Radiographs revealed that the lateral side of the right proximal tibial growth plate had closed, although other growth plates (proximal fibula and distal femur) were still open	Chronic Salter–Harris Type V injury from repetitive compression, shearing, valgus and varus forces on the knee resulting in premature (partial) closure of the lateral side of the right proximal tibial growth plate	Exploratory surgery and histology showed degeneration of fatty bone marrow with increased vascularity, and reactive osteoblasts and cartilage herniation into the bone resulting in compression injury to the growth plate. Patient started to play basketball again 5 months after surgery
Domzalski and Mackenzie 2008 [111]	2 M Basketball	14	Basketball was the predominant sport played in both patients	Radiographs and MRI revealed symmetrical closure of the proximal tibial physes (left knee in one boy and right knee in the other). Tibial shortening present in both patients	Premature closure of the proximal tibial physis resulting in progressive recurvatum and valgus deformity of the knee. Repetitive trauma or chronic overloading during sports activities led to growth arrest	Gradual correction using Taylor Spatial frame with excellent results at 2 year follow-up, although no indication of if/when return to activity occurred

Table 2 (continued)

Sport/study	No. of Subjects	Mean age/age range	Activity	Imaging findings (X-ray, MRI)	Diagnosis	Treatment
Laor et al. 2006 [21]	1 F Tennis	11.5	Chronic overuse knee pain associated with competitive tennis	Radiographs revealed physeal widening of both medial distal femoral physes and both medial proximal tibial physes Frontal photograph obtained 6 years later shows relative varus alignment of her lower extremities	The girl was noncompliant and developed bilateral varus deformity of the knees	The patient continued vigorous tennis training. At 50 months after her initial clinic visit, she had persistent knee pain. She had developed bilateral varus deformity of the knees, already visible at 24 months
Nanni et al. 2005 [118]	1 M Rugby	15	2-month history of increasing pain and swelling affecting the medial aspect of the right proximal tibia He had been intensely practicing his kicking skills on a daily basis and continued despite the pain and swelling	Radiographs and MRI showed wide separation of right proximal tibial physis, asymmetrically affecting the medial side more than the lateral side. Entire metaphyseal margin adjacent to the physis was irregular and there was metaphyseal sclerosis. There was secondary varus deformity of the femur	Salter–Harris type 1 injury of the proximal tibial growth plate in response to extreme rotational and pressure forces on the epiphysis during the practice of rugby ball kicking. Secondary varus deformity of the femur	Conservative treatment (e.g., ice, strapping) led to no significant improvement. Osteotomy restored lower limb alignment (varus opening wedge osteotomy of the right distal femur). Uneventful recovery, with return to playing rugby 6 months after surgery
Dempewolf et al. 2019 [120]	3 M Soccer	14–14.5	All adolescents presented with activity-related right knee pain isolated to the medial aspect of the knee. All participated in competitive year-round soccer leagues. One patient also participated in American football as a place kicker. All were right leg dominant, which was their "kicking leg." Pain was activity-related and mild/moderate in severity	Radiographs showed a widened and irregular lateral femoral physis	Atraumatic lateral distal femoral hemi-physeal arrest with resultant ipsilateral genu valgum deformity, arising from repetitive valgus stress caused from kicking a soccer ball or football, causing repetitive compression and damaging of the lateral physis	All patients underwent medial hemiepiphysiodesis and guided growth which was successful in correcting the mechanical axis in 2 of the 3 adolescents The adolescent who failed to correct was treated with a lateral distal femoral opening osteotomy that successfully realigned his limb. All 3 patients returned to competitive soccer

Table 2 (continued)

Sport/study	No. of Subjects	Mean age/age range	Activity	Imaging findings (X-ray, MRI)	Diagnosis	Treatment
Ankle/foot						
Shybut et al. 2008 [123]	1 F Dance	12	The patient presented complaining of right forefoot pain. At this time, she had been involved in an extensive curriculum of Flamenco dance lessons, practice, and performance for over 2 years. During this period, she rehearsed or performed 10 or more hours per week	Radiographs revealed a widened and irregular second metatarsal physis which over the next 13 months showed premature closure, producing relative shortening of the second metatarsal	Second metatarsal premature physeal arrest due to repetitive vibratory stress associated with Flamenco dancing	The patient was treated conservatively with restricted weight-bearing and crutches and allowed to return to dance training after 3 months. At this time, radiographs showed persistence of the physeal irregularity and widening. At 6-month follow-up, her physis began to show evidence of bony bridging. She was pain-free and was participating in Flamenco. At 13 months, radiographs showed premature closure and radiographic shortening consistent with growth arrest of the second metatarsal. At the time of latest follow-up, the patient had returned to dancing, albeit at a lesser intensity
Shah 2017 [126]	1 F Ballet	13	Ballet dancer presented with a 2 years history of a shortened right second toe. She reported no history of injury, pain, or trauma to the feet. She began dancing ballet at the age of 3 years. At the time of her visit, she was dancing at a preprofessional ballet school, 2–3 h/day, 5 days/week	Radiographs and MRI of the right foot revealed a shortened second metatarsal and growth plate closure of the head of the second metatarsal of the right foot	Premature growth plate arrest of the second metatarsal head physis from dancing en pointe. Shortened second toe. Excessive stress from dancing en pointe was considered to be the offending mechanism	To help distribute the force of dancing en pointe from the first toe to the second toe, the author instructed her to purchase a cap to place on the second toe. She noted that this modification in her pointe shoe enabled her to dance comfortably with a noted benefit of relieving some of the weight-bearing off the first toe

CT computerized tomography, *MRI* magnetic resonance imaging, *M* male; *F* female, *LLS* Little leaguer's shoulder, *PIP* proximal interphalangeal joint

Fig. 6 Fourteen-year-old female gymnast with chronic right wrist pain. Reproduced from Caine et al. [130], with permission. **A** Asymptomatic left wrist. **B** Symptomatic right wrist showing partial closure of the right distal radial physis, centrally and ulnarly, producing ulnar positive variance. The ulnar physis remains open

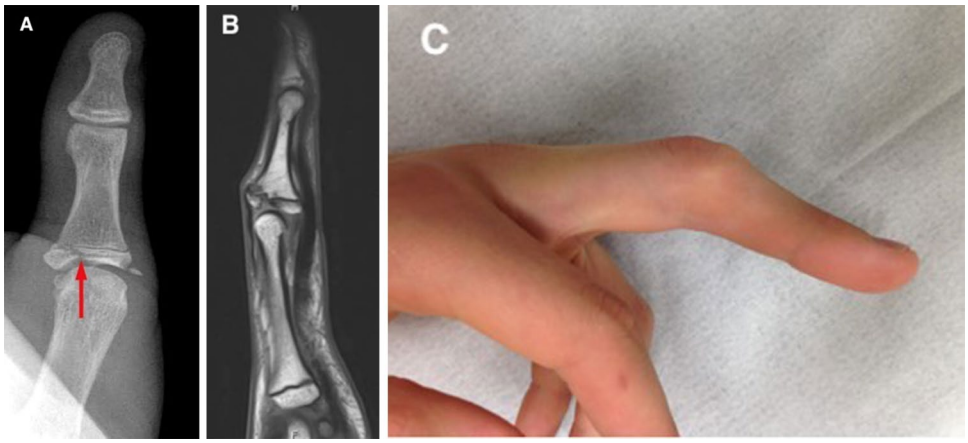

Fig. 7 A 15-year-old climber with chronic pain in the proximal interphalangeal joint of his middle finger. **A** Radiograph and **B** sagittal magnetic resonance image of an old and malaligned growth plate fracture involving the middle phalanx of the middle finger. **C** A picture of the hand showing swelling and deformity of the proximal interphalangeal joint of the middle finger

in one case series study [26] and one case–control study [135]. Notably, none of the cross-sectional studies focused or otherwise reported on lower extremity PPSIs among skeletally immature athletes.

Perusal of Table 3 reveals a wide range of training and competitive levels including recreational athletes [133, 148], club-level competitive athletes [26, 134, 135, 139, 142–144, 149, 150], specialized training school [27, 141], and elite- or national-level competitive athletes [136–138, 140, 147–150]. Although prevalence estimates of PPSIs are reported in most of these studies, comparison of these studies is compromised by differences in how and whether symptoms were reported.

3.3.1 Unknown Symptomatology

In imaging studies which did not report current or past symptoms, the prevalence of radiographic abnormalities consistent with PPSIs ranged from 5 to 83% [27, 51, 135, 137, 139, 140, 148, 149]. Athletes in this category included baseball players (prevalence range 0–21.7%) [133, 135], divers (52.6%) [136], gymnasts (10–83%) [27, 137, 139, 140], and climbers (5–47%) [148, 149, 151]. Notably, the prevalence of stress reaction (e.g., subchondral sclerosis/increased thickness of physis) was greater in German Junior National Team (GJNT) climbers (47%) than recreational climbers (RC) (28%).

3.3.2 Proportion of Asymptomatic Cases with PPSIs

One study reported prevalence of radiographic abnormalities consistent with PPSIs in skeletally immature athletes who were asymptomatic [26]. Roy et al. [26] reported minimal widening and irregularity of the distal radial growth plate in 30.8% of asymptomatic club-level competitive gymnasts.

3.3.3 Proportion of Symptomatic Cases with PPSIs

Among skeletally immature athletes who were symptomatic (with positive history of pain and/or current pain), the prevalence of PPSI was 36.6% among youth baseball players [134], 58% among competitive youth climbers [150], and 72.4% among nationally ranked youth climbers [147].

3.3.4 Proportion of Prevalent PPSIs that were Symptomatic

Another approach has been to report the proportion of prevalent cases of PPSIs which were characterized by a positive history of related symptoms [142–144]. DiFiori et al. [142] reported a 25% prevalence of PPSIs among club-level gymnasts and that 81.8% (9/11) of these reported a history of wrist pain. However, a similar proportion of those without radiographic evidence of PPSI (25/33; 75.8%) also had wrist pain. In a follow-up study of competitive gymnasts, DiFiori et al. [143] reported a prevalence of 51% of stress injury to the distal radial physis of at least grade 2 (one or more of the following: cystic changes, metaphyseal sclerosis, striations, or beaking of the metaphysis). In this study, wrist pain prevalence was significantly related to the grade of radiographic injury. Finally, Guerra et al. [144] reported a 65% prevalence of wrist physeal injury among club-level competitive gymnasts; of these, 82% were symptomatic.

The healthy distal radial physis is characterized by a thin center surrounded by thicker borders [145]. Notably, Kraan et al. [145] reported that of the ten gymnasts with the highest distal radial physeal volumes in their study, nine were symptomatic. These results are consistent with those of Zhang et al. [136] who found a significantly greater thickness of the epiphyseal plate in skeletally immature divers with radiographic evidence of PPSI (Group A) compared to those without irregular widening (Group B), and with controls (Group C) ($A > B > C$; $P = 0.0001$).

Several cross-sectional studies provide further insight into the potential for growth disturbance and deformity associated with PPSI in select groups of skeletally immature athletes, with prevalence rates of PPSIs associated with growth disturbance ranging from 1.7 to 5.0% [27, 141, 147, 149].

Shih et al. [27] reported partial closure of the distal radial growth plate with bridge formation in the left radius of two (2/47; 4.3%) gymnasts. Chang et al. [141] reported three (3/176; 1.7%) Chinese Opera students who showed early partial closure of the distal radial physis. Notably, students with fused physes in this study had a mean ulnar variance which was significantly greater in gymnasts when compared to the control group ($P < 0.05$); 8.2% (14 of 170 wrists) had exceedingly large ($> +3$ mm) ulnar positive variance [141].

Among youth climbers, Schlegel et al. [147] reported one patient (1/29;3.4%) with premature closure of the physis of the proximal phalanx of the thumb, while Garcia et al. [149] reported MRI evidence showing early transphyseal bone bridging in a skeletally immature climber (1/20;5%) which can lead to finger-shortening and angular deformities. Notably, Bartschi et al. [150] reported that among 16 youth climbers seen in their practice for epiphyseal pain between 2006 and 2018, and in whom the index injury was left untreated, 8 climbers (8/16; 50%) developed growth plate damage and articular surface incongruency with permanent impairment of the injured finger.

3.4 Cohort Studies

Compared to cross-sectional studies (numerator-based designs), prospective and historical studies (denominator-based designs) provide the best opportunity to provide data designed to answer the question regarding "how big is the problem?" Unfortunately, most cohort studies of injuries affecting youth athletes fail to provide details related to overuse injuries, particularly PPSI [152, 153].

Our review uncovered only a handful of cohort studies which reported data on PPSIs [5, 130, 154–158] (Table 4). In these studies, calculated clinical incidence of PPSIs was 4.4 per 100 athletes among baseball players [154], and ranged from 1.27–71.4 PPSIs per 100 athletes among gymnasts [130, 155–157], with the highest clinical incidence reported among elite-level gymnasts monitored regularly over 9 years [155]. Comparability of these results is compromised, however, since clinical incidence rates do not account for potential variation in exposure of participants to risk for injury [159]. Although Schöffl et al. [5, 158] reported only one PPSI in their follow-up studies of youth climbers, the clinical incidence of stress reaction of the fingers of GJNT members in these studies was 80 per 100 participants.

Based on their single-season shoulder MRI-based study of Little League baseball players, Holt et al. [154] reported that eight players (34.8%) had new or worsening findings on their post-season MRI when compared to preseason MRI. MRI findings included partial rotator cuff tear (5), proximal humeral periphyseal edema with physeal widening (1), labral tear (1), and acromioclavicular joint edema.

Four cohort studies report PPSIs sustained by competitive male and/or female gymnasts [130, 155–157]. Lishen and Jianhua [155] reported on injuries affecting elite Chinese gymnasts followed clinically and with routine radiography over nine years (1972–1980). During the follow-up period, 6 of 18 girls and 8 of 10 boys (14 patients total, including 6 with bilateral injuries = 20 wrists) developed progressive wrist pathology including periphyseal stress changes of the distal radial growth plate with accompanying decreased range of motion at the wrist. Eventually, radiographs revealed hindered radial growth and a relatively lengthened ulna, and findings of posttraumatic osteoarthritis (OA) in

Table 3 Cross-sectional studies reporting prevalence of primary periphyseal stress injury

Study	n	Age range	Study results	Prevalence
Baseball				
Torg et al. 1972 [133]	49 M Recreational pitchers in regional championships	9–18	Radiographic examinations were performed on the shoulders and elbows of 44 of 49 recreational pitchers. There were no abnormalities detected in the shoulders of any pitchers. Thirteen pitchers (29.5%) reported episodes of shoulder pain; however, the pain did not cause anyone to seek medical attention or prevent further participation	0% (none injured)
Kanematsu et al. 2015 [134]	2055 M Regional championships	9–12	275 (13.5%) players reported episodes of pain of the throwing shoulder. Forty-one of 275 (14.9%) agreed to undergo radiographic examination. Of these 41, 15 (36.6%) were diagnosed with LLS. Of these 15, 9 showed widening of the physeal plate in the lateral area, 5 had diffuse widening of the physeal plate and demineralization of the metaphysis, and 1 showed a slipped epiphysis	36.6% *in players with history of shoulder pain
Pennock et al. 2018 [135] CC	23 M Little league players	10–12	12 players (52%) had 17 positive MRI findings in their throwing shoulder that were not present in their non-dominant shoulder (e.g., increased edema or widening of the proximal humeral physis, labral tear, partial-thickness rotator tear). Five players (21.7%) showed edema or widening of the proximal humeral physeal plate	21.7% asymptomatic
Diving				
Zhang et al. 2017 [136]	Provincial diving team 22 F 16 M Controls 14 F 11 M	Divers: 10–17 Controls: 10–17	Using MRI of both wrists, twenty-nine cases (29/76, 38.15%) of irregular widening of the distal radial growth plate were observed in 20 divers (Group A). Group B (18 divers) without irregular widening. Distal radial epiphyseal plate injury (MRI showing irregular widening of the physeal plate and sclerosis on the metaphyseal side) were observed in 20 divers (20/38, 52.63%). The incidence of injury to the right hand was higher than that for the left ($P=0.009$). There were statistically significant differences ($P<0.05$) among the 3 groups in terms of physeal plate thickness; group A > group B > group C	52.6% of asymptomatic divers with growth plate injury
Gymnastics				
Auberge et al. 1984 [137]	41 M 57 F European national championships	14–17 11–15	Radiographic imaging of the left wrist revealed chronic osteo-articular lesions involving the distal extremity of the radius in 83% of gymnasts	83%
Szot et al. 1985 [138]	41 M Elite competitive	15–31	Radiographs revealed that thirteen gymnasts (32%) had subjective complaints related to the wrist. However, distal radial epiphyseal irregularities were found in 58.5% of the group	58.5%
Roy et al. 1985 [26] CS	26 F Club-level competitive	9–14	Radiographic evaluation of the distal radius revealed minimal widening and irregularity of the distal radial growth plate in 30.8% of the gymnasts studied	30.8% asymptomatic
Caine et al. 1992 [139]	39 F 21 M Competitive club-level	9–17 9–18	Radiographs revealed minimal widening and irregularities of the distal radial physis (10%). Definite changes of subchondral sclerosis, physeal widening, marginal new bone formation, and distortion of the distal end of the radius (4.8%)	10.0%
DeSmet et al. 1994 [140]	156 F National level	13–20	Radiographs revealed enlargement of the distal radial growth plate with irregular borders in 10.3% of the cases	10.3%
Chang et al. 1995 [141]	Study group 143 F 118 M Controls 44 F 19 M	10–19	Unfused group: radiographs showed 42/176 MF (23.9%) with stress-related changes (physeal widening, sclerosis, partial closure) of the distal radial growth plate (10 F; 32 M). Three cases showed early partial closure of the distal radial growth plate Fused group: radiographs showed that mean ulnar variance was significantly greater in gymnasts compared to the control group ($P<0.05$); 8.2% (14 of 170 wrists) had exceedingly large (> +3 mm) ulnar plus variance	23.9% 24.6% of symptomatic wrists were injured vs. 10.5% of asymptomatic wrists

Table 3 (continued)

Study	n	Age range	Study results	Prevalence
Shih et al. 1995 [27]	10 F 37 M	10–16	MRI findings in 92 wrists: growth plate widening ($n = 17$), physeal cartilage extension to metaphysis ($n = 17$), physeal cartilage extension to epiphysis ($n = 7$), metaphyseal bone bruise ($n = 17$), horizontal fractures ($n = 23$), and vertical fractures ($n = 8$). Partial closure of the distal radial growth plate with bridge formation was found in the radial aspects of the left radius of two girls, ages 12 and 13. Radiographic abnormalities of the distal radii in 29/92 radii (31.5%) ($n = 17$)	31.5%
DiFiori et al. 1997 [142]	17 M 27 F Club-level competitive	5–16	11 gymnasts (25%; M/F) showed radiographic evidence consistent with stress injury to the distal radial physis. 9 of these 11 subjects reported history of wrist pain (81.8%). However, this finding was not significantly different from those without wrist pain (25 of 33 = 76%; $P = 0.70$). Ulnar variance was found to be more positive in the gymnasts than age-matched controls	25.0% 9/11 (81.8%) were symptomatic
DiFiori et al. 2002 [143]	28 F 31 M Club-level competitive	5–16	Wrist pain was reported in 56% of gymnasts (33 of 59) with 45% (15 of 33) describing pain for at least 6 months duration. Radiographic evaluation revealed that fifty-one percent of the gymnasts (30 of 59) had findings of stress injury to the distal radial physis of at least a grade 2; 7% had frank widening of the growth plate. The prevalence of wrist pain was associated with the radiographic grade of distal radial physeal injury ($P = 0.007$)	51.0%
Guerra et al. [144]	19 M Club-level competitive	9–18	Radiographs revealed that 65% of gymnasts had wrist physeal injury; 82% of these gymnasts had wrist pain (uncorrelated data). Signs of injury on the growth plate included: widening of the distal radial physis, metaphyseal bone cysts, wedging distal epiphysis and blurring of the radiolucent physis	65.0% 53 (82%) were symptomatic
Kraan et al. [145]	36 M 33 F Elite	13.4–15.1	Volume measurements were performed on MRI images by creating three-dimensional physeal reconstructions. Median physeal volume was significantly increased ($p < 0.05$) in symptomatic ($n = 27$; 971 mm^3) and asymptomatic ($n = 18$; 951 mm^3) gymnasts compared with non-gymnasts ($n = 24$; 646 mm^3). Of the ten participants with the highest physeal volumes, nine were symptomatic gymnasts	Gymnasts with highest physeal volumes were symptomatic
Kraan et al. [146]	35 M 31 F Elite	13.6–14.4	Symptomatic gymnasts with clinically suspected overuse injury of the distal radial physis and age and gender-matched asymptomatic gymnasts and healthy non-gymnasts underwent MRI of the wrist. In symptomatic gymnasts ($n = 27$) increase in physeal thickness was most prominent at the volar side when compared to asymptomatic gymnasts ($n = 16$) and non-gymnasts ($n = 23$). Physes of healthy non-gymnasts had a thin center and increased in thickness towards the borders	Greatest physeal thickness seen in symptomatic gymnasts
Rock climbing				
Schlegal et al. 2002 [147]	26 M 3 F nationally ranked	10–17	The climbers were divided into two groups: group 1 included those with current pain in the finger ($n = 21$) and group 2 was free of pain ($n = 8$). In group 1 16/21 climbers had clinical and/or radiographic abnormalities. Radiographically, four athletes (4/21) were found to have abnormalities in the epiphysis of PIP joints of the fingers indicating a possible injury at or near the epiphysis. One climber showed a premature closure of the physis of the proximal phalanx of the thumb. These radiological findings could be considered as signs of incomplete epiphysiolysis after repetitive microtrauma	19.0% (symptomatic group)

Table 3 (continued)

Study	n	Age range	Study results	Prevalence
Schöffl et al. 2004 [148]	GJNT: 4 F 15 M RC: 2 F 16 M	GJNT: 16.2 ± 1.7 RC: 14.7 ± 1.9	In 47% of the GJNT and 28% of RC, adaptive stress reactions could be found on radiographs: cortical hypertrophy (26% GJNT, 11% RC), subchondral sclerosis/increased thickness of physis (47% GJNT, 6% RC), broadened joint base PIP (42% GJNT, 28% RC), and broadened joint base DIP (16% GJNT, 0% RC). Signs of early osteoarthritis were seen in 5% of GJNT and 6% of RC (1 case of physeal fracture in each group). Osteoarthrosis was defined if a Kellgren and Lawrence grade ≥ 2 was present. One case of epiphyseal stress fracture was seen in each group	5.3%
Garcia et al. 2018 [149]	20 (8 M/12 F Competitive rock climbers 6 non-climbers (3 M/3 F)	10–17 11–15	Ultrasound (US) was used in all subjects. In four climbers with finger deformity or pain, 3-T MR images were compared with US findings. Lack of alignment of the metaphysis with the epiphysis was found in 20% of climbers. Growth plate abnormalities were identified in 3/9 of the most advanced level three climbers. In a 12-year-old climber, a fracture involved the physis and epiphysis (Salter–Harris type III) in the middle phalange. In a 17-year-old climber, the fracture involved the epiphysis. In another climber, the MRI demonstrated early physeal bone bridging. In this same climber, a growth plate stress injury was noted in the distal metacarpals, which was not symptomatic and not seen on US	20% Malalignment 33.3% (3/9) growth plate abnormalities
Bartschi et al. 2019 [150]	21 M 7 F Competitive climbers	13.7	Twenty-eight climbers with physeal pain treated between 2006 and 2018 were included in the study. Sixteen patients completed a questionnaire addressing injury details as well as training regimen before and after the injury. Radiographs showing physeal stress fractures (Salter–Harris II/III) in the proximal interphalangeal joint of the middle finger in 14 climbers (11 M; 3 F) and ring finger in 2 climbers (2 M). Chronic stress and microfractures are the main etiological factors of this injury. Most patients had a positive outcome with treatment and rest. However, in 8/28 patients, where the injury was left untreated, there was growth plate damage and moderate joint incongruity with permanent impairment of the affected finger	58.0% (16/28) All symptomatic
Meyers et al. 2020 [151]	139 M 128 F Elite youth climbers	9–18	A survey of adolescent climbers who competed in the 2017 USA Climbing Sport and Speed Youth National Championships. Questions assessed climbing injury history and current rock-climbing training characteristics. 267 (43.6%) adolescent competition climbers completed the survey. Among these participants, 12 (5%) reported a history of a finger growth plate injury (58% male, 42% female)	5% (12/267)

CC Case–control study (includes cross-sectional data), *CS* case series (includes cross-sectional data), *GJNT* German Junior National Team, *LLS* Little League Shoulder, *M* male, *F* female, *MRI* Magnetic resonance imaging, *PIP* Proximal interphalangeal joint, *RC* Recreational climbers, *US* Ultrasound

Table 4 Cohort studies reporting primary periphyseal stress injuries

Study	Design characteristics	No. subjects	Age	Study results	Clinical incidence
Baseball					
Holt et al. 2020 [154]	Prospective cohort (1 season pre- and post- comparative screening) Little league players	23 M	10–12	14/23 players (60.9%) had positive dominant shoulder MRI findings not present in their non-dominant shoulder. Eight players (34.8%) had new or worsening post-season findings including 1 case of periphyseal edema with physeal widening. Other MRI abnormalities included supraspinatus tear, infraspinatus tear, and acromioclavicular edema	4.4 PPSIs per 100 athletes
Gymnastics					
Lishen and Jianhua 1983 [155]	Prospective cohort (1972–80) Elite-level competitors	18 F 10 M	11–12 13–15	14/28 gymnasts (6 F, 8 M) experienced 20 stress injuries involving the distal radial growth plate. Most notable among the radiographic changes observed was the loss of normal anatomic relationship between the radius and the ulna (i.e., length discrepancy), leading to a separation of the radioulnar joint and arthritic changes. This occurred in 16/20 of the injuries	71.4 PPSIs per 100 athletes
Caine et al. 1989 [156]	Prospective, cohort (1986–87) Club-level competitors	50 F	9–17	43/50 gymnasts sustained 147 injuries; incidence = 294 injuries per 100 athletes. Four injuries involved the distal radial growth plate (e.g., stress syndrome, bilateral irritation, epiphysitis)	8.0 PPSIs per 100 athletes
Dixon and Fricker 1993 [157]	Retrospective cohort (1982–1991) Elite-level competitors	42 M 74 F	12–22 9–19	116 M/F gymnasts sustained 572 injuries; incidence = 493 injuries per 100 athletes; 3 injuries involved the distal radial growth plate of female gymnasts (i.e., physeal stress injuries)	4.1 PPSIs per 100 female participants
Caine et al. 2003 [130]	Prospective Cohort (1993–96) Club-level competitors	79 F	7–18	60/79 gymnasts (76%) sustained 192 injuries while 19/79 (24%) remained injury-free. One gymnast underwent an ulnar shortening procedure with plate fixation for premature closure of the right distal radial physis	1.27 PPSIs per 100 participants
Rock climbing					
Schöffl et al. 2007 [158]	Prospective (1999–04) GJNT competitive climbers	GJNT: 6 M 4 F RC 8 M 2 F	1999: 16 2004: 21 1999:14.8 2004:21.6	Radiographs revealed adaptive stress reactions (e.g., cortical hypertrophy, increased thickness of the physis, subchondral sclerosis) in fingers of 8/10 of GJNT in both 1999 and 2004 and increased in the RC from 2 of 10 (1999) to 3 of 10 (2004). One climber in the RC group who had an epiphyseal fracture in 1999 had a normal radiograph in 2004	Only one RC PPSI which healed during follow-up
Schöffl et al. 2018 [5]	Prospective (1999–2011) GJNT competitive climbers	GJNT: 19 M/F RC 18 M/F	1999: 16.5 ± 1.9 years 2011: 14.7 ± 2.3 years	15/19 climbers in the GJNT group and 13/18 climbers in the RC group were re-evaluated at a mean follow-up time of 11.3 ± 1.2 years. Radiographic stress reactions of the hand (e.g., cortical hypertrophy, increased thickness of the physis, subchondral sclerosis), considered adaptive changes, were found in 80% of the GJNT group and 46% of the RC group. Signs of early stage osteoarthritis were seen in 6 climbers in 2011: 4 (27%) in the GJNT group and 2 (15%) in the RC group. In comparison, these signs were found in only 1 GJNT climber and no RC climbers in 1999	No reports of PPSIs in the hand and fingers

GJNT German Junior National Team, *M* male, *F* female, *M/F* number of males and females combined, *MRI* magnetic resonance imaging, *RC* Recreational climbers

the wrist joints. However, the authors did not indicate the criteria for OA.

Caine et al. [156] reported 147 injuries affecting 50 U.S. club-level female gymnasts over 1 year. Dixon and Fricker [157] reported a total of 572 injuries affecting a total of 162 Australian elite male and female gymnasts over a 10-year period. Notably, chronic injuries represented 44.2% and 39.0% of all injuries in the U.S. and Australian gymnasts, respectively [156, 157].

Although the studies of American and Australian gymnasts reported on injuries affecting all body regions, only upper extremities PPSIs of female athletes were reported in these studies (4 and 3 PPSIs affecting the distal radius of American and Australian gymnasts, respectively). In contrast, Caine et al. [130] found only 1 PPSI in their 3-year study of club-level gymnasts. Notably, unlike their previous study [156], access to medical records of gymnasts was not provided in this study.

Two studies of youth climbers indicate that adaptive stress reactions in the fingers of competitive climbers are common [5, 158]. Schöffl et al. [158] conducted a 5-year radiographic follow-up study of GJNT and recreational rock climbers with data points in 1999 and 2004. Although adaptive stress reaction of the phalangeal periphyseal area was prevalent among recreational climbers on both occasions, only one climber developed a PPSI. No climbers in this study developed OA (as defined by a Kellgren–Lawrence grade ≥ 2).

In their 11-year follow-up of the GJNT rock climbers (2 data collection points: 1999 and 2011), Schöffl et al. [5] found that both of the PPSIs recorded in 1999 (one in the GJNT) had healed without consequences. In 2011, adaptive stress reactions were found in 12 of 15 (80%) of the GJNT compared to 15 of 19 (79%) of the GJNT in 1999. Signs of early stage OA were seen in 4/15 of the GJNT climbers (27%) in 2011 compared to 1/19 (5%) in 1999. Significant statistical association was found between the development of early onset OA and overall total training years ($P = 0.024$), use of campus board training in 1999 ($P = 0.033$), and climbing level ($P = 0.030$).

Data from several studies of youth climbers indicate an increase in proportion of finger PPSIs over time [102, 107, 109]. Over a 2-year period (2017–18). Lutter et al. [109] conducted a clinical follow-up study of injuries among 436 climbing patients. They compared these data with two prior study populations followed during 1998–2001 [107] and 2009–2012 [102] and found an increase in the proportion of finger PPSIs. Finger PPSIs were seen in 0.8% of cases between 1998 and 2001 [107], 3.4% of all cases during 2009–2012 [102], and were present in 7.3% of all finger injuries during 2017–2018 [109].

4 Discussion

4.1 Injury Occurrence

A primary purpose of this systematic review was to describe the present status of knowledge on the occurrence of PPSIs affecting children and adolescents involved in youth sports. Our review uncovered data from case reports and series, case–control, cross-sectional, and cohort studies which provide important information related to this question.

4.1.1 Case Reports/Series

Overall, our review includes 101 case reports/case series describing 448 patients with PPSIs involving the shoulder, elbow, hand and wrist, knee, ankle and foot. Most patients were male (73%), likely reflecting the greater participation of male than female patients, especially in baseball. Patients representing a variety of sports and high impact repetitive activities—including baseball, badminton, climbing, cricket, dance, gymnastics, rugby, soccer, swimming, tennis, and volleyball—may sustain PPSIs. Although youth participating in advanced or elite-level sports appear particularly at risk, skeletally immature non-elite and recreational athletes were not spared from incurring PPSIs [5, 133, 142, 148, 158].

A limitation of case reports and case series is that these studies provide no information on the population at risk and therefore cannot be used to generate prevalence or incidence rates. However, the sheer volume of cases reported raises concern regarding the extent of PPSI occurrence among youth. A logical question follows: what is the rate of PPSI among skeletally immature athletes?

4.1.2 Cross-Sectional Studies

Results from cross-sectional studies (see Table 3) indicate a troubling prevalence of PPSIs in select groups of skeletally immature competitive athletes—including baseball players (shoulder: 0–36.6%), divers (wrist: 52.6%), gymnasts (wrist: 10–85%), and rock climbers (fingers: 17.2–58%). The only cross-sectional study reporting no patients with PPSI was a radiographic study of youth recreational pitchers [133]. Notably, no cross-sectional studies reported on PPSIs affecting the lower extremity of skeletally immature athletes.

The prevalence of PPSIs reported in the cross-sectional studies was variable depending on whether symptoms were unknown (5–83%), whether patients were asymptomatic (30.8–52.6%), or symptomatic (36.6–72.4%), and on the proportion of cases that were symptomatic (51–81.8%). Notably, not all youth with radiographic or MRI findings consistent with PPSI are necessarily symptomatic. Furthermore,

this does not account for the fact that the presence or absence of "symptoms" is subjective, and athletes may under-report their symptoms due to concerns over the inability to continue their sport.

A limitation of the cross-sectional studies reviewed is that they typically include only subjects available at the time of the survey. Thus, for example, individuals with PPSI and associated pain may not be represented in the study sample, because they dropped out earlier (i.e., the survey is of "survivors" only).

4.1.3 Cohort Studies

Only a few cohort studies (see Table 4) reported prospective or retrospective data on PPSIs affecting youth, including baseball players, gymnasts, and rock climbers [5, 130, 154–158]. Using count data, these studies reported from 1 to 20 incident cases of PPSI arising during study follow-up ranging from one season to 12 years. Since data did not permit calculation of PPSI incidence for these studies, we calculated clinical incidence of PPSIs from the available data; these ranged from 1.7 to 71.4 PPSIs per 100 athletes [154–157]. The highest rate of PPSIs was documented in elite gymnasts who were monitored radiographically over 9 years [155]. A limitation of these results is that clinical incidence does not account for the potential variance in the exposure of participants to risk of injury [159].

Historically, the frequency and incidence of traumatic growth plate fractures and PPSIs have been underreported in cohort studies of youth sports injuries [15, 160]. These injuries have traditionally been included in other categories of injury such as fractures or overuse injuries [15, 153]. Additionally, overuse injuries are underestimated in the literature as most of the epidemiological studies define injury as requiring a time loss from participation [13]. Consequently, the number and nature of PPSIs have not been explicitly reported in epidemiological studies of youth sports injuries. In response to this oversight, the International Olympic Committee recently published a consensus statement on methods for recording and reporting of epidemiological data on injury and illness in sport recommending that "physis injury" (including apophyseal injuries) should be a separate category of tissue and pathology types of injury [161]. Important to this approach will be the distinction between primary periphyseal (site of long bone growth) and apophyseal (contribute to bone shape) injuries [15], and between sudden and gradual onset injuries in each sub-category.

4.1.4 Trend Analysis

Several clinicians have observed an increasing number of patients with PPSIs treated in their clinical practices and suggest that these cases may be on the rise [10, 13, 18, 127, 162]. In Fig. 2, we showed a general pattern of increased number of original PPSI reports published per decade between 1950 and 2019. Heyworth et al. [31] showed that the incidence of LLS treated at a regional children's hospital increased significantly in the period 1999–2013. Also, Lutter et al. [109] reported an increased proportion of finger PPSIs in skeletally immature rock climbers seen at a medical center over a 20-year period (1998–2018).

It is reasonable to expect that the frequency or rate of PPSIs is increasing given the trends discussed previously [1–5]. However, it is also possible that the increased reporting of patients with PPSIs is a reflection of the explosive nature of medical publishing and international research activity, rather than an actual epidemiological phenomenon. Increased reporting of PPSIs may also reflect an increasing public health and clinical awareness of the potential for this injury type. There remains a concern that PPSIs constitute a growing problem among youth athletes, but epidemiological studies are needed to investigate this possibility.

4.2 Injury Outcome

A secondary purpose of this systematic review was to describe the present status of knowledge on the outcome of PPSIs affecting youth sports participants. To elucidate on the outcome of PPSIs, we reviewed data on injury management, presence of growth disturbance, use of surgery, and potential long-term health effects of PPSI.

4.2.1 Injury Management

The nature and extent of information provided on injury management varied considerably across studies. However, some generalizations are possible. In the case literature reviewed, PPSIs were almost universally treated with rest from the exacerbating activity to allow healing. In many patients, rest from the activity included time off from the sport followed by a gradual return to activity. Length of time off before return to activity was variable, ranging from 1 week to 13 months, depending on factors such as injury location, injury severity, whether the patient underwent surgery, and timing of initiation of treatment relative to injury onset.

When necessary, joint immobilization was prescribed to ensure sufficient rest. A variety of treatment modalities were used to ensure the rest of the affected structure including slings, splinting, casting, crutches, knee immobilizers, ankle bracing, and shoe modification. Some studies also reported the use of physical therapy and programs to improve strength, range of motion, and movement mechanics.

Reasonably, initiation of physical therapy and progressive rehabilitation programs should await symptom resolution and, preferably, radiographic evidence of healing, noting that

it may lag behind clinical improvement by weeks to months. For example, Laor et al. [21] caution that children with physeal widening in the knee from a stress injury should not undergo physical therapy and progressive rehabilitation as they would risk subsequent malalignment [21]. Similarly, it has also been suggested that the injured throwing athlete does not return to pitching activity until the proximal humeral physis had fused [33, 34, 36, 56], while others stress that the athlete should be asymptomatic before return to play [32, 37, 45].

4.2.2 Bone Growth Disturbance

A concern with PPSIs is their potential for skeletal growth disruption and future deformity [10, 15–17]. Most case reports and case series of PPSIs reviewed indicate that this injury resolved with rest during short follow-up and did not produce growth disturbance or deformity. However, as summarized in Table 2, there were 57 cases (12.7%) of disturbed skeletal growth arising from the case reports/series that provide imaging evidence of bone growth disturbance involving the shoulder, elbow, wrist, hand and fingers, knee, foot and ankle of skeletally immature athletes. Sports impacted by these injuries include baseball, basketball, dance, football, gymnastics, rock climbing, and rugby. Additionally, symmetric blunted growth across the growth plate may go unrecognized and underdiagnosed when the duration of follow-up is short (insufficient time to produce limb-length discrepancy) and direct comparison with the asymptomatic (non-dominant side) is unavailable to allow detection of subtle shortening.

Several cross-sectional studies provided evidence of growth disturbance of the distal radius in gymnasts [27] and Chinese opera students [141], and in the proximal phalanx of the thumb and proximal interphalangeal joint of climbers [148, 150]. In these studies, calculated prevalence rates of PPSIs associated with bone growth disturbance ranged from 1.7 to 5.0% [27, 141, 147, 149].

Only two cohort studies reported evidence of bone growth disturbance. Among incident injuries reported, Caine et al. [130] reported a gymnast with premature closure of the right distal radial growth plate. Lishen and Jianhua [155] reported six of eight female and eight of ten male gymnasts followed with routine radiography over 9 years (1972–80) who developed progressive pathology of the distal radius resulting in hindered radial growth and a relatively lengthened ulna [155].

These results make sense according to existing biologic knowledge as, in experimental studies, prolonged intensive physical loading is associated with inhibition of linear bone growth [163–166]. This injury may be localized and cause asymmetric growth and secondary deformity, or it may involve the entire physis and result in hindered growth or a complete cessation of growth. In either case, premature closure of some or all of the physis may occur [18, 24].

4.2.3 Surgery

Of the 448 patients treated for PPSIs, as reported in the case reports and series, 28 patients (6.2%) underwent surgery for their injury. With the exception of one patient who was treated surgically [37], 196 patients with PPSIs involving the shoulder were treated conservatively. Similarly, only 1 patient with a PPSI of the foot and ankle was treated surgically [125]. In contrast, 11/47 patients with elbow PPSIs, 8/98 patients with wrist PPSIs, and 7/26 patients with knee PPSIs were treated surgically to correct growth disturbance and/or secondary deformity (e.g., proximal radial osteotomy, ulnar shortening osteotomy, open wedge osteotomy of the right distal femur, and surgically guided growth).

Information on time to return to activity following surgery was not uniformly provided in the studies reviewed, generally indicating considerable variation depending on such factors as injury location and type of surgery performed. Time to return to activity following surgery appeared to be greatest for the knee (range = 5–24 months) followed by the wrist (range = 1–15 months) and fingers ($\geq$ 3 months).

4.2.4 Long-Term Health Outcome

PPSIs can counter the beneficial effects of sports participation at a young age if the child or adolescent is unable to continue to participate as a result of the residual effects of injury [13, 14, 150]. Although not consistently reported in the case literature, return to the sport and eventually at former levels of participation following treatment of PPSIs was common. Nevertheless, some patients found it necessary to change position, for example from pitcher to fielder [32, 37, 43, 56], or participate at a less competitive level following PPSI [92, 123]. There are also reports of patients who retired from their sport pursuant to PPSI [65, 66, 69, 70, 74, 75, 84, 87], or who were otherwise lost to follow-up [43, 46, 81, 88, 129].

A concern related to PPSIs is that acquired limb-length discrepancy, angular deformity, or altered joint biomechanics may cause significant long-term morbidity and disability [163]. Specifically, OA may result from chondral damage at the time of growth plate injury, articular incongruity, or joint malalignment [14]. For example, leg length inequality of the lower extremities, a condition which may contribute to the development of radiographic knee and hip OA by causing asymmetrical joint mechanics between limbs during weight-bearing activities, may arise from a stress-injured physis [167–169]. To compensate for leg length inequality, movement patterns may differ between limbs (i.e., the longer limb may exhibit greater knee flexion or

hip adduction during stance than the shorter limb to attempt to functionally shorten the longer limb) [170]. Changes in movement patterns to equalize limbs may result in altered or magnified forces across lower extremity joints, leading to the development of OA [171].

Limited longitudinal research involving elite-level gymnasts [155] and rock climbers [5, 17, 158] attests to the potential for early onset OA to develop secondary to PPSIs in skeletally immature athletes. However, the incidence of sport-related PPSIs leading to early onset OA is largely unknown [171]. Follow-up of stress-injured youth athletes into their early adult years is needed to examine this relationship [14, 171].

5 Conclusions

Skeletally immature athletes representing a variety of sports and high impact repetitive activities—including baseball, badminton, climbing, cricket, dance, gymnastics, rugby, soccer, swimming, tennis, and volleyball—may sustain PPSIs involving the shoulder, elbow, hand and wrist, knee, ankle and foot.

Although incidence data from prospective cohort studies are lacking, data arising from cross-sectional studies suggest that PPSIs may be common in select groups of youth athletes—including the shoulder in baseball players, wrist in gymnasts and platform divers, and fingers in rock climbers. Multiple case reports and case series report PPSIs affecting the lower extremity, including those associated with bone growth disturbance; however, no cross-sectional studies focused on lower extremity PPSIs.

Most reported PPSIs appear to respond well to timely treatment, but our research also revealed multiple cases which progressed to skeletal growth disruption and deformity. Of particular concern are PPSIs which affect weight-bearing joints given their potential for growth disruption. Establishing a clear diagnosis of PPSI and providing timely treatment is of great significance in ensuring the skeletal health of skeletally immature athletes. Prospective longitudinal studies, with imaging follow-up, are needed to better elucidate the incidence of PPSIs and how these may impact long-term musculoskeletal health. In this regard, explicit inclusion of PPSIs as an injury type in injury surveillance is essential.

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Declarations

Conflict of interest Dennis Caine, Rachel Meyers, Jie Nguyen, Volker Schöffl, and Nicola Maffulli declare that they have no competing interests.

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Data availability statement Supplementary information in the form of six summary tables (Supplementary Information Tables S1–S6) is available to authorized users [see title page for information] or from the author on request. These summary tables correspond to results discussed in Sects. 3.2.1–3.2.6.

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