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ORIGINAL PAPER

Mechanism and predisposing factors for proximal tibial epiphysiolysis in adolescents during sports activities

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Abstract

Background Proximal tibial epiphysiolysis (PTE) can have debilitating consequences for young athletes. The mechanism and predisposing factors for this lesion have yet to be determined. To find a common denominator and a biomechanical explanation for PTE, we were using a retrospective analysis of 15 cases in combination with a systematic review of literature.

Methods A retrospective review of medical charts was performed to identify all PTE between 2003 and 2012. Records were screened for patient age and gender, sports activity, mechanism of injury, and treatment protocols. Additionally, a literature review (MEDLINE/PubMed database, the Cochrane Library, online search engines) was conducted.

Results Medical charts of 14 adolescents (15 Salter-Harris I and II fractures) were analyzed. The literature review revealed additional 75 fractures. The predominant mechanisms were landing from a jump, takeoff for a jump, stop and go movements, and eccentric muscle contraction with the knee in flexion. The main sports-activities implicated in these injuries were basketball.

Conclusions Landing from a jump with a decreased knee and hip flexion movement increases tensile forces on the proximal tibia epiphysis. During physiological epiphysiodesis, the growth plate displays an increased vulnerability and such increased tensile forces can lead to a growth plate failure. Neuromuscular fatigue can alter coordination and proprioceptive accuracy during landing from a vertical jump and thus perturbs sagittal shock absorption. In our opinion, trainers should instruct young athletes in techniques that help avoiding uncontrolled high impact landings.

Level of evidence: Level IV.

Keywords Proximal tibial epiphysiolysis · Atypical physeal fracture · Physeal sports injury · Adolescent · Growth fracture · Low-energy fracture

Introduction

The knee joint is subjected to strong leverage forces and relatively unprotected by surrounding muscles and soft tissue. Nevertheless, proximal tibial fractures are rare injuries, representing 1.8% of all fractures of long bones in the paediatric population [1] and when considering all physeal fractures the reported incidence of this lesion is only 0.8% [2]. The proximal physis of the tibia is well protected by different structures that circumferentially reinforce the perichondrium. Anteriorly, the tibial tubercle overhangs the adjacent metaphysis acting as an effective block to posterior displacement [3]. On the lateral side, the proximal tibial epiphysis is buttressed by the upper part of the fibula. Medially, the superficial layer of the collateral ligament inserts distal to the physis into the upper metaphysis, while the insertion of the semimembranosus muscle spans the physis in the posteromedial corner. Finally, the sloped shape of growing cartilage in itself provides good stability to the proximal tibial epiphysis [4].

Physeal separation of the proximal tibia may be caused by a direct trauma (motor vehicle accident, direct impact against the tibia during sport), an indirect force (rotation of the knee while the foot is fixed to the ground, tackling in soccer), or by an indirect mechanism consisting of avulsion forces due to muscle contraction (sudden stop, muscle contraction during landing or during takeoff). As the latter mechanism of proximal tibial epiphysiolysis is considered a rare injury [5–8], the scientific literature concerning this subject is limited. There

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are some similarities to the mechanism of injury of tibial tubercle avulsion-fractures and the proximal tibial epiphysiolysis. In 1955, Watson-Jones [9] described three types of tibial tubercle avulsion-fractures based on the extent of displacement of the fracture fragment of the proximal tibial epiphysis. Years later, Ryu and Debenham [10] published a case of a complete physeal separation where they suspected forces were propagated from the tibial tubercle through the epiphyseal line to the posterior cortex or metaphysis. They suggested adding it as a type IV avulsion-fracture in the Watson-Jones classification. To our knowledge, there are some case reports in the medical literature concerning non-contact PTE [10–32], but few describe a possible mechanism or predisposing factors for this lesion.

We report on a series of 15 PTE occurring during sportive activities without any direct force other than muscle contracture. In the present report, we try to give a biomechanical explanation for these lesions occurring essentially during landing impact or during the takeoff phase of a jump.

Methods

Case series

After board approval (Mat-Ped 09-022R), a retrospective review of medical charts was performed to identify all children and adolescents who had been treated for a proximal tibial epiphysiolysis at our institution between January 2003 and December 2012. Collected data concerned patient demographics (age and gender), sports activity at the time of injury, mechanism of injury, previous knee trauma, and treatment protocols. The radiographic review included plain radiographs, Computed Tomography (CT) scans, and Magnetic Resonance Imaging (MRI). Patient bone age was calculated on a left hand and wrist X-ray according to the Greulich and Pyle radiographic atlas.

Literature review

A search of the MEDLINE/PUB MED databases and the Cochrane Library search engine was conducted without date restriction until December 31, 2014. The keywords used in different combinations were "p(a)ediatric," "child," "children," "adolescent," "proximal," "tibia," "epiphysiolysis," "epiphyseal," "physis," and "fracture." Various Internet search engines were also screened for web pages with further references. Articles in English, French, German, and Italian were accepted. The title of each article identified by the above search terms was surveyed, and abstracts were reviewed if the title appeared to be relevant. Full-text reviews were conducted if the article was deemed potentially eligible for inclusion. The reference list of all articles meeting the inclusion criteria was searched for additional relevant articles, which were subjected to the same screening process. All titles, abstracts, and full text articles were reviewed by both authors and an agreement was reached in all cases.

Selection criteria

Inclusion criteria

Proximal tibia epiphyseal or physeal fractures in children and adolescents (< 18 years of age) with an open growth plate of the proximal tibia. Fractures had to be acquired during sports activities without direct trauma against the proximal tibia.

Exclusion criteria

Exclusion criteria are as follows: other types of proximal tibia fractures or pathological fractures, fractures due to direct trauma to the knee or fractures involving only the tibial tubercle, high-velocity sports injuries, injuries not acquired during sports or leisure activities, and no individual case description or non-interpretable content.

The literature analysis was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [33] (Fig. 1). Twenty-four articles were considered relevant with respect to identifying demographics (age and gender), sport responsible for injury, mechanism of injury, type of fracture using the Salter-Harris classification and treatment protocols. The total number of patients included in this review was 84 presenting a total of 90 lesions. The study represented Level 4 evidence according to the CEBM (Centre for Evidence-based Medicine) classification, and this evidence yielded only a Grade-C recommendation on both the CEBM and SORT (Strength of Recommendation Taxonomy) scales.

Results

Cases

A total of 84 cases accounting for 90 fractures were evaluated in this study (Table 1). Fractures were classified according to Salter-Harris (SH) (9 SH I, 74 SH II, 7 SH IV).

Our own patients accounted for 14 cases with a total of 15 proximal epiphysiolyses of the tibia. Four patients sustained SH type I fractures, the remaining 11 lesions were classified as SH type II fractures (Table 1). All patients were male with an average age of 14.67 ± 1.2 years. The radiological bone age was between 14½ and 15½ years. The left knee was affected in nine cases and the right in six cases. One patient presented with a bilateral fracture (Fig. 2a–d). None of the patients reported previous knee trauma. All patients presented at the

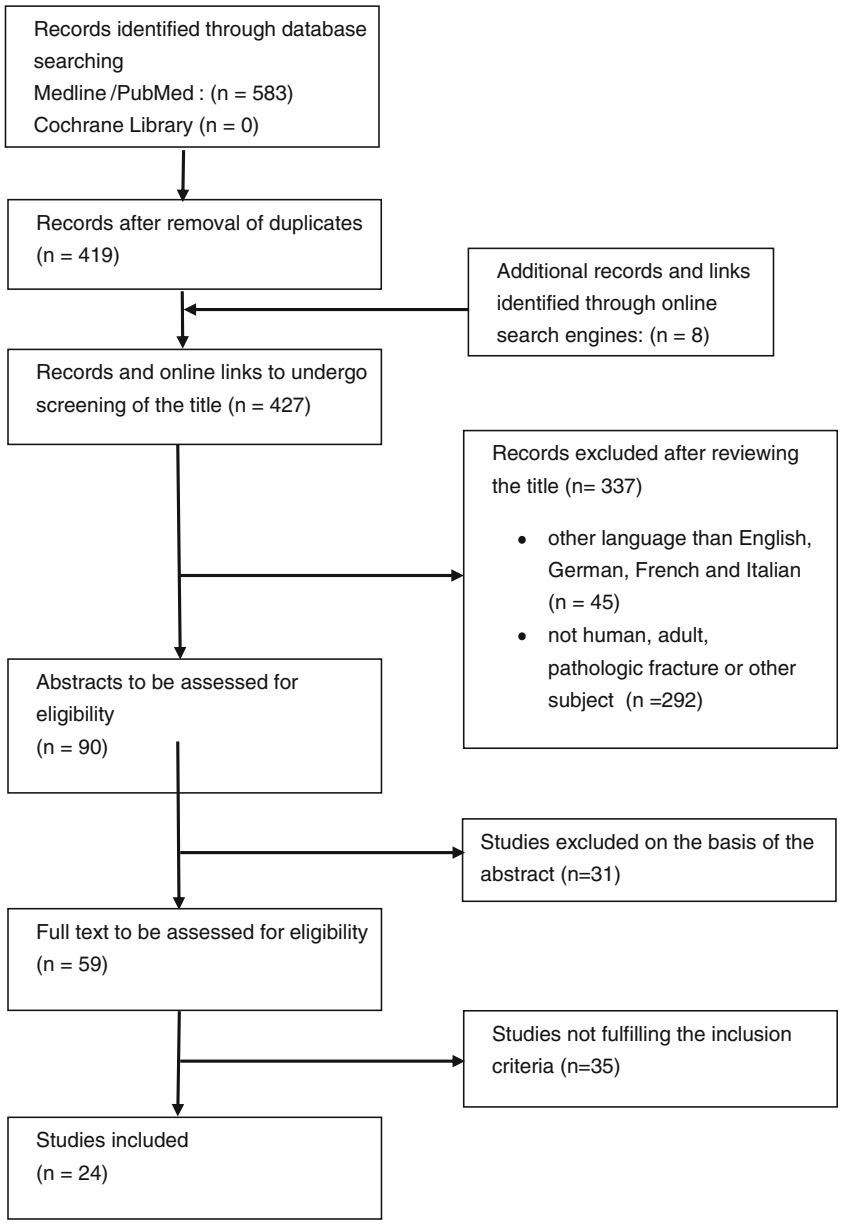

Fig. 1 PRISM flowchart

emergency department with proximal anterior tibial pain, swelling, and functional disability of the knee. No patient had signs of a lower leg compartment syndrome. Standard radiographic examination with additional oblique X-ray at 45° did not show a fracture in two patients. As there was a high clinical suspicion of a non-displaced fracture an MRI of the knee was performed which confirmed the diagnosis (Fig. 3a–e). Treatment consisted of closed reduction and percutaneous screw stabilization, closed reduction, and casting or simple casting for non-displaced fractures. No complications during or after the treatment were observed; There were no leg length differences or angular leg deformities in our patient cohort. All patients were followed up until physiologic epiphysiodesis was completed bilaterally.

Literature review

The conducted literature review revealed 24 studies fulfilling the defined inclusion criteria. Data of 70 patients with a total of 75 fractures were evaluated. Fractures were 63 times classified as SH type II, seven times as type IV, and 5 times as type I. Fifty-seven patients were male, four female, and nine times no information concerning gender could be found.

Combined data analyses

For the demographic data analyses, our own cases and cases from the literature review were reviewed together. Mean patient age was calculated for each fracture group giving a mean age of 12.6 years (range 8–13 years) for the SH I group,

Table 1 Patient demographics; L (left), R (right), ND (not determined), CR (closed reduction), PC (percutaneous), ORIF (open reduction internal fixation), CRPP (closed reduction percutaneous pin)

Author	Number and gender of patients	Mean Age	Affected side	SH classification	Associated sports activity	Mechanism of injury	Treatment
Steiger C	14 Male	14.7	8 Left 5 Right 1 Bilateral	11 Type II 4 Type I	12 Basketball 1 Soccer 1 High jumping	12 Landing 1 Takeoff 1 Blocking of the kicking foot 1 Eccentric contraction	3 Cast 7 CR and PC screws 5 CR and cast
Pace JL	20 Male 3 Female	15	7 Right 15 Left 1 Bilateral	21 Type II 3 IVB	10 Basketball 4 Soccer 4 Fall 2 Gymnastics 1 High jumping 1 Running hurdles 1 Trampoline 1 ND	ND	5 CRPP 19 ORIF
Andriessen MJG	1 Female	14	1 Bilateral	2 Type II	2 Trampoline	ND	2 CR and cast
Kraus R	1 Male	13	1 Left	1 Type I	1 Soccer	ND	1 CR and PC screws
Patari SK	2 Male	14	1 Right 1 Left	2 Type IVB	1 Cycling 1 Fall	ND	2 ORIF
Takai S	2 Male	13.25	1 Right 1 Left	1 Type II 1 Type I	1 Basketball 1 ND	2 Takeoff	2 CR and cast
Mudgal CS	1 Male	16	1 Left	1 Type I	1 Basketball	1 Takeoff	1CR and PC screws
Özokyay L	1 Male	14	1 Left	1 Type II	1 Running	ND	1 CRPS/cast
Käfer W	1 Male	13	1 Right	1 Type II	1 Long jump	ND	1 CRPP
Burkhart SS	7 ND	12.6	ND	1 Type I 6 Type II	2 Sledding 2 Football 1 Cycling 1 Gynmastics 1 Basketball	ND	7 CR and cast
McGuigan JA	1 Male	13	1 Left	1 Type II	1 Fall	1 Hyperextension	1 Splint
Bertin KC	1 Male	14.83	ND	1 Type II	1 Football	ND	1 CR and cast
Vyas S	5 Male	14.6	4 Left 1 Right	1 Type II 4 Type II	2 Basketball 1 Soccer 1 American football 1 Fencing	2 Takeoff 1 Landing 1 Direct blow to the knee 1 ND	5 CR and cast
Inoue G	5 Male	15.6	2 Right 3 Left	5 Type II	2 Long jump 2 High jumping 1 Basketball	3 Takeoff 2 Landing	5 CR and cast
Donahue JP	1 Male	17	1 Right	1 Type II	1 Basketball	1 Landing	1 CR and PC screws
Blanks RH	2 Male	16.5	ND	2 Type II	1 Basketball	2 Landing	2 CR and cast
Merloz P	1 Male	15	1 Bilateral	2 Type II	2 Basketball	Running	2 CR and cast
Ryu RK	1 Male	16	1 Left	1 Type II	1 Basketball	1 Takeoff	1 CR and cast
Trepte CT	4 Male	14.5	2 Right 2 Left	3 Type II 1 Type IV	1 School sports 2 High jumping 1 Warm up running	1 Landing 2 Takeoff 1 Running	2 CR and cast 1 CRPP 1 ORIF
Bracker W	1 Male	15	1 Left	1 Type II	1 High jumping	1 Takeoff	1 CRPP
Rappold G	1 Male	16	Bilateral	1 Type II 1 Type I	2 Somersault	2 Takeoff	2 CR and cast
Jalgaonkar AA	1 Male	13	1 Right	1 Type IV	1 Basketball	1 Takeoff	1 ORIF
Omar M	1 Male	16	Bilateral	2 Type II	2 Soccer	2 Kicking the ball	2 ORIF
Baxmann T	1 Male 1 ND	15.5	1 Left 1 Right	2 Type II	1 football 1 running	1 Unbalanced landing 1 Fall	1 ORIF 1 CRPP
Fung BKK	3 Male	15.3	2 ND 1 Left	3 Type II	2 basketball 1 Soccer	3 ND	2 CR and cast 1 cast
Crimaldi S	1 Male	17	1 ND	1 Type II	1 Soccer	1 Flexed knee with contracted quadriceps	1 CRPP

Table 1 (continued)

Author	Number and gender of patients	Mean Age	Affected side	SH classification	Associated sports activity	Mechanism of injury	Treatment
mean age SHI		12.6					
mean age SHII		14.9					
mean age SHIV		13.9					
Total number of fractures		90 (including 6 bilateral fractures)					
Total number of patients		84					

14.9 years (range 12–17 years) for the SH II group, and 13.9 years (range 12–15 years) for the SH IV fracture group. Accident mechanisms causing PTE were identified. The four predominant mechanisms were landing from a jump, takeoff for a jump, stop, and go movements and eccentric muscle contraction with the knee in flexion (full data in Table 1). The main sport activities implicated in these injuries were basketball (41%), high and long jumping (11%), and soccer and football (18%). Other activities accounted for 30% of injuries (Table 1).

Of the 90 fractures 42 (47%) that were treated non-operatively by cast immobilization with or without preceding closed reduction, 22 (24%) fractures required closed reduction and percutaneous pinning or screw stabilization and 26 (29%) fractures were treated with open reduction and internal fixation (Table 1).

Discussion

Epiphysiolysis or epiphyseal fracture-separation of the proximal tibia is an uncommon injury which seems to occur exclusively in adolescents. The epiphysis undergoes posterior

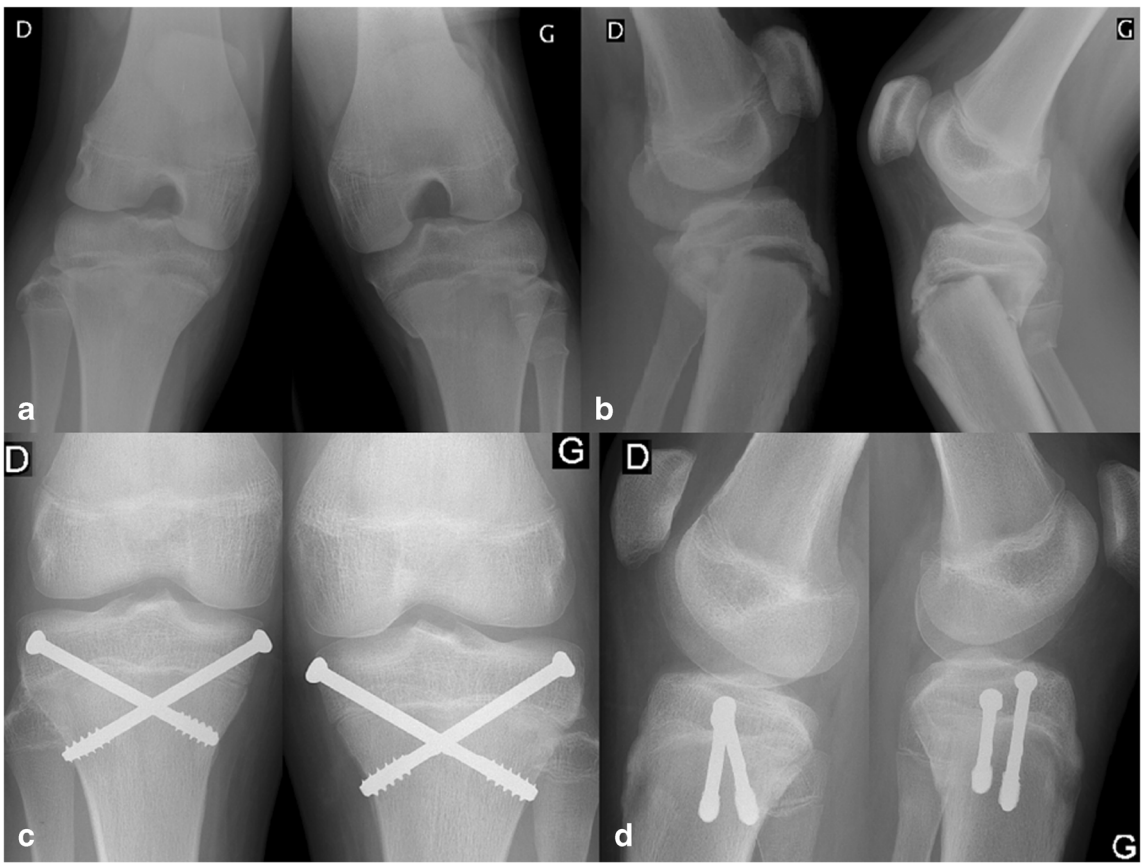

Fig. 2 (a) anterior-posterior (ap) and (b) lateral radiographs from a 13 year-old male teenager presenting with a bilateral PTE (SH II). The adolescent described a sudden bilateral knee pain when landing from a jump during a basketball game. The fracture remained unstable after closed reduction. Due to an advanced bone age (15 years) osteosynthesis with percutaneous screws was chosen. (c) and (d) show the ap and lateral radiographs after closed reduction and percutaneous screw osteosynthesis

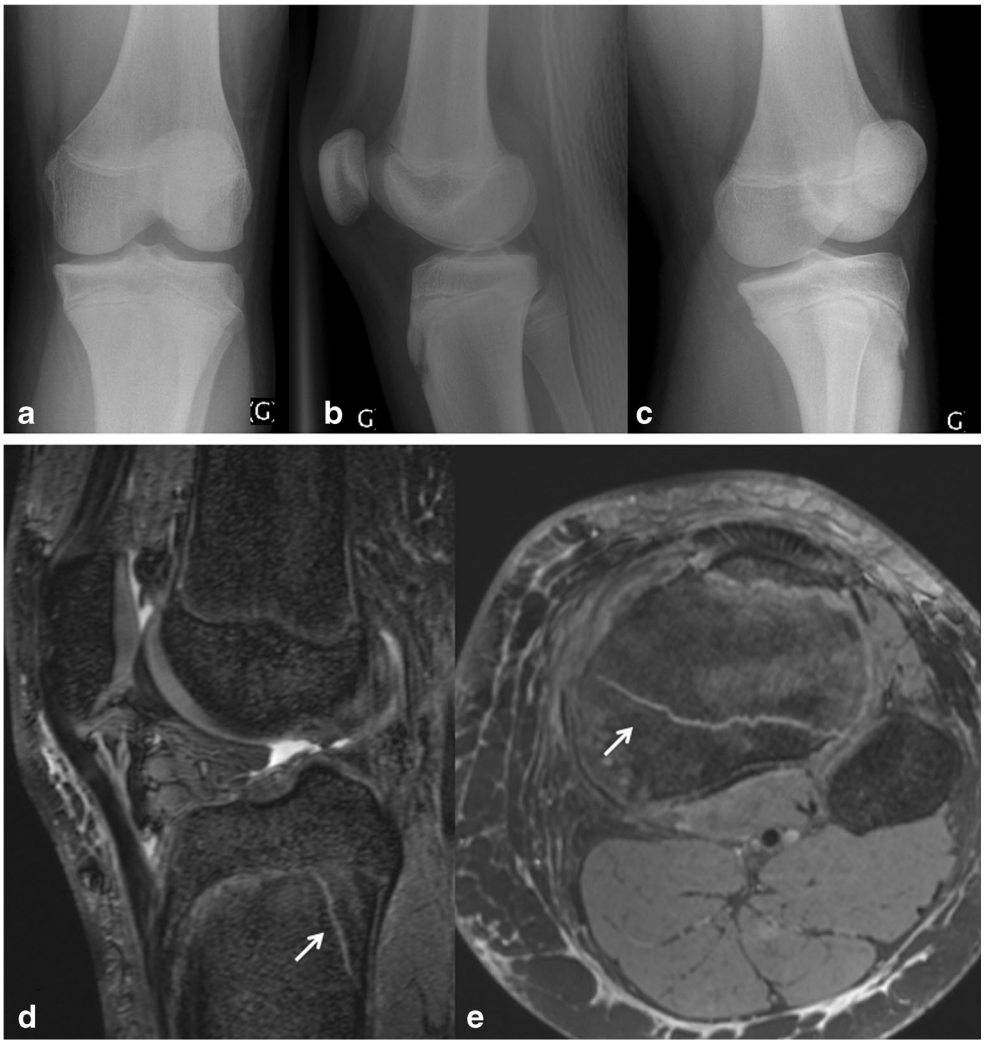

Fig. 3 (a) anterior-posterior (ap), (b) lateral, and (c) oblique radiographs from a 13-year-old male teenager presenting with knee pain after landing from a jump during basketball practice. Standard radiographs did not reveal a fracture. A complementary MRI scan (d and e) confirmed a non-displaced SHII fracture of the proximal tibia (white arrow)

displacement, while the fracture line follows the physis, and may extend into the metaphysis (Fig. 2a, b) [10, 11]. This lesion must be clearly differentiated from proximal physeal fractures due to forceful hyperextension or abduction injuries that may occur during a high-energy collision in sports or motor vehicle accidents. In the latter, a posterior displacement of the tibial metaphysis relative to the epiphysis has been described [8]. Furthermore, these injuries may be associated with vascular complications due to the proximity of the popliteal artery [3, 8, 9].

While high energy trauma resulting in tibial physis fractures concerns adolescent boys and girls in equal numbers there is a clear gender predisposition for the non-contact type epiphysiolysis of the proximal tibia. In fact, the majority of injured adolescents in the discussed publications (including our own data) were male (71 patients) aged between 13 and 17 years, while girls were rarely affected and accounted only for 4 cases. This unbalanced gender repartition is most likely due to sports activities performed at the age at which physeal closure take place.

In our study and in our literature review, we found basketball, high and long jumps, and soccer as sports posing a high risk for physeal fractures. Basketball was the predominant sports activity associated with SH type I and type II fractures. As these injuries occur without major trauma in teenagers within a narrow age range, it suggests that the proximal tibial physis might become vulnerable during the growth spurt [30].

Physeal fusion starts with a coalescence of the tibial apophysis and the tibial metaphysis and is followed by a fusion of the epiphysis and the proximal tibia in a posterior to anterior direction. From a histological point of view, physeal fibrocartilage is gradually replaced at the end of the epiphyseal stage by a zone of provisional calcification causing a physiologic epiphysiodesis. At this time, the epiphysis is most vulnerable to disruptive tensile forces and thus the likelihood of an epiphysiolysis is highest [34]. The underlying mechanism is the hormonal change during puberty which initiates loosening of the physeal cartilage and prepares for physiological closure [6, 35]. Puberty and thus ossification of the proximal tibial physis takes place at a younger age in girls than in boys.

Therefore, the time at risk for physeal fractures is at a younger age in girls than in boys.

Basketball, soccer but also athletics, and sports which are strenuous for the knee, are more frequently practiced by male than by female adolescents. Competitive training in these sports activities starts at high-school age and is gradually intensified every year. While female adolescents have already reached the puberty peak in the first few training years and reach closure of their physis at moderate training intensity (13–14 years of age), boys reach high-intensity training stages with still partially open growth plates (15–16 years of age). In addition, strength training is practiced regularly to enhance jumping and running capacity. This, however, leads to increased muscle forces applying tensile forces to the proximal physis. Although strength training is practiced by both, male and female athletes, it has been shown that adolescent boys have higher strength values than adolescent girls, especially in the lower limbs (*Measures of Muscular Strength in US Children and Adolescents*, 2012). Thus, we believe that the male predisposition of physeal fractures is due to a combination of increased muscle force and practicing a sport with frequent stop and go activities or powerful takeoff and landing movements at the time of highest vulnerability of the physis. Female athletes are less frequently affected as physeal closure has already finished at the time of high-intensity training. In fact, juvenile ACL injuries occur more frequently in girls than in boys. While growth plates fuse earlier in female athletes, female leg muscle strength is inferior to their male colleges. Thus, when high sheer forces pass though the knee stress is primarily applied to the ACL and not the physis, however, muscle force to balance knee movements is often not sufficient to prevent injury.

To date the mechanism of non-contact and low-energy proximal tibial physis fractures has been discussed only by few. As the injury is relatively rare, previously published studies have been either retrospective analyses of patient files [20, 27] or case reports [10–14, 16–19, 21–26, 28–32, 36–38]. While documentation for case reports was generally quite detailed, retrospective studies often lacked data concerning accident mechanism, practiced sports activity and clinical examination. Limb position at the time of injury and the exact sequence of events are often neglected during primary patient evaluation. Our department has a keen interest regarding sports related injuries of the lower extremity and such injuries are thus meticulously documented which enabled us to further develop existing hypotheses and to add new aspects regarding the mechanism of this injury. The earliest biomechanical description of PTE found in medical literature dates back to the mid-sixties and was made by Silberman and Murphy [15]; for them, proximal tibial epiphysiolysis was due to an indirect traumatism by sudden flexion of knee or during athletic activities requiring a "push off." In accordance with this, others have proposed that this lesion represents an avulsion injury, the mechanism being an overload of tensile forces on the epiphysis when the knee is kept in flexion during the takeoff phase of a jump [11, 12, 20, 32]. Thus these lesions have also been named flexion-avulsion fractures. However, the mechanism of avulsion in flexion only explains fractures taking place during the takeoff phase of a jump or a sudden stop with the knee in flexion. In basketball, the sports activity most frequently leading to this injury, the majority of teenagers described landing from a jump as the cause of injury. During landing from jumps in basketball, the knee is often in extension, making the flexion avulsion theory as only mechanism of injury rather unlikely. We hypothesize that the primary mechanism of non-contact physeal fractures is spontaneous unbalanced intense muscle contraction either during landing or during the takeoff phase.

Several recent biomechanical reports have demonstrated that landing from a vertical jump or "stop-jump"-moves with high impact forces are a risk factor for adolescent knee injuries, particularly for non-contact anterior cruciate ligament injuries [39–41]. Although landing from a jump and stop jumps are frequently performed moves in sports, they are often poorly executed by children and teenagers leading to a high incidence of sports-related knee injuries in this patient group [42]. During landing impact or abrupt stops eccentric muscle contraction takes place. From a biomechanical view, the muscle lengthens against resistance during eccentric contraction, meaning that it absorbs energy. Thus, in eccentric muscle contraction, the total force directed at the muscle is greater than in concentric contractions [43].

Literature suggests that elevated knee flexion during the landing phase reduces the risk of injury due to lower ground reaction forces and better shock absorption [44, 45]. Proper energy absorption with a correct knee and hip flexion movement will decrease the vertical ground reaction force, and therefore, the harmful proximal tibia anterior shear force [46, 47]. While adolescents with closed physes are at risk for ACL injuries when landing with knees in extension, younger children might suffer from PTE.

In our opinion, the same principle described for the landing phase also applies for the push off stage in the takeoff phase of powerful jumps. Just before takeoff, the knee is in extension with both quadriceps and hamstrings at peak contraction. As the balancing force of the hamstrings is reduced in this extension position, anterior sheer forces are transferred through the knee. While the ACL might be strong enough to resist rupture in older adolescents, the physis is prone to dislocation. Thus, resulting fracture at the beginning of the epiphyseal stage is the SH type I. SH type II and type IV fractures are seen in advanced maturation during the epiphyseal stage when the posterior part of the physis has already fused but the anterior part is still open.

Landing performances in sport activities have been investigated in detail to prevent lower extremity injuries [48–52].

Contributing factors to the frequency and severity of injuries include impact forces and torques, body position at landing, and landing surface [51]. Fatigue has recently been documented as another risk factor for knee injuries. Neuromuscular fatigue alters knee and hip flexion control as well as proprioceptive acuity [53]. Indeed, some studies demonstrated that lower extremity muscle fatigue significantly increased the peak anterior shear force on the proximal tibia of recreational athletes, especially when performing stop-jump tasks [54, 55]. While adult athletes are probably more conscious to their own limits and recognize muscle fatigue, children are prone to train even when close to exhaustion. Thus, close observation of fatigue in sportive adolescents is imperative.

The clinical importance of determining an accident mechanism has previously been shown for many sports injuries and in particular for the ACL (reviewed in [56]). Once a mechanism of injury is understood, preventive measures can be taken [57]. Video-analyses of training sessions and jumping evaluation in gait labs help to develop sport-specific training programs. Improvement of muscle balance and exercises reenforcing knee control during stop and go activities and during jumping/landing maneuvers is of uppermost importance. Neuromuscular training enhances proprioception and is thus essential in preventing injuries. Furthermore, trainers require specific instructions to recognize dangerous knee positions during high-risk movements so that they can intervene before injuries occur.

Conclusion

PTE is an injury affecting predominantly male teenagers at the time of the epiphyseal stage of bone maturation. The triggering event seems to be forceful eccentric contraction of the quadriceps and the hamstrings during landing or before jumping generating enough tensile forces for growth plate failure. Sports activities predisposing to this injury are basketball, long and high jump, and soccer. As the consequences of an epiphysiolyis are potential growth arrest and axis deviation of the leg, prevention of this injury is important. Thus, we strongly recommend that teenage athletes undergo specific training of vertical jumping, in order to improve coordination and to attenuate tensile forces during the landing phase. As lower extremity muscle fatigue is another recognized risk factor for knee injuries, trainers have to take care not to push athletes beyond their physical capacity. Proprioceptive training in combination with strength training improves physical preparedness and avoids injury due to uncoordinated movements.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval Geneva ethics board approval (Mat-Ped 09-022R).

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