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PICTORIAL ESSAY

Avulsion fractures of the pediatric knee

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Abstract Although avulsion fractures of the pediatric knee are uncommon, they are important injuries to recognize because they are frequently associated with adjacent soft-tissue and osteocartilaginous abnormalities. Related injuries, which include entrapment of soft-tissue structures, intra-articular fracture extension, and intra-articular loose bodies, can complicate or alter therapy. The most commonly affected soft-tissue structures include the cruciate ligaments, collateral ligaments and supporting tendons, and extensor mechanism and retinacula. The purpose of this pictorial essay is to review avulsion fractures of the pediatric knee and to highlight associated injuries.

Keywords Knee · Fracture · Avulsion · Pediatric · Children · Magnetic resonance imaging · Radiography

Introduction

An avulsion fracture typically results from an acute tensile force on a ligament or tendon that overcomes the stress capacity of the bony attachment [1]. The immature skeleton often responds differently to such stresses compared to the mature musculoskeletal system. Specifically, the osteocartilaginous interfaces and adjacent newly formed bone are the weakest links in the growing skeleton, whereas in adults, the musculotendinous junctions are most often injured [2]. Therefore, acute tensile forces in children frequently result in avulsion injuries at or near osteochondral interfaces.

Among growing children, adolescents are most vulnerable to avulsion fractures because of their increase in muscle strength and relative weakness of osteocartilaginous junctions. As a result of adjacent strong muscle contractions and numerous soft-tissue attachment sites, the bones about the knee are particularly susceptible to such injuries [1]. Commonly involved structures in the pediatric knee include the cruciate ligaments, collateral ligaments and supporting tendons, and extensor mechanism and retinacula. Specific injuries associated with avulsion fractures that may replace conservative therapy (such as casting) with operative management include entrapment of soft-tissue structures, intra-articular fracture extension, and intra-articular loose bodies. This pictorial essay reviews the variety of avulsion fractures of the pediatric knee and highlights their radiologic patterns and associated soft-tissue injuries, in addition to other potential therapy-altering complications.

Avulsion fractures involving the cruciate ligaments

Anterior cruciate ligament

Anterior cruciate ligament (ACL) injuries most commonly are mid-substance tears affecting female athletes who are approaching or have completed skeletal maturity. However, the same mechanism of injury that would result in an ACL tear in an older patient may cause an acute avulsion fracture of the

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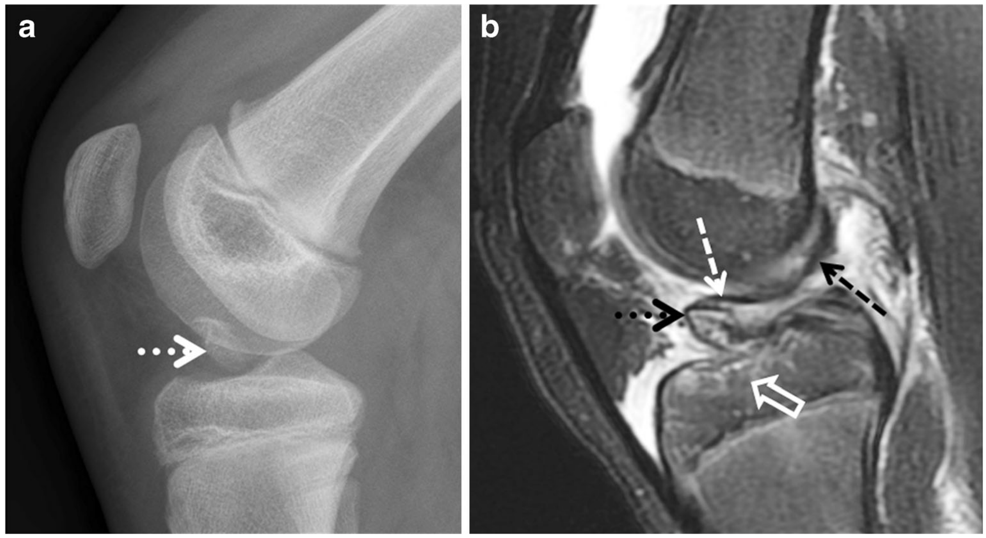

Fig. 1 Intercondylar eminence avulsion in an 8-year-old girl who fell from a bicycle. **a** Lateral radiograph and (**b**) sagittal fat-saturated T2-W MRI show a mildly displaced bone fragment (*dotted arrows*) in the intercondylar notch arising from the distal ACL attachment on the tibial epiphysis. This is consistent with a type III intercondylar eminence fracture. The ACL is intact (*dashed arrows* in **b**). There is minimal marrow signal abnormality subjacent to the donor site (*open arrow* in **b**). *ACL* anterior cruciate ligament

distal ACL attachment at the tibial intercondylar eminence in skeletally immature children, typically boys 8–14 years of age (Figs. 1, 2, 3 and 4) [2, 3].

Intercondylar eminence fractures have been classified into three types by Meyers and McKeever [4] based on the degree of osteochondral fragment displacement: type I is nondisplaced, type II is posteriorly hinged with elevation of the anterior component of the fragment, and type III is displaced [3]. Adjacent soft tissues, including the transverse intermeniscal ligament and anterior horn of the medial or lateral meniscus, may become interposed between the fracture fragment and donor site (Figs. 2 and 3), preventing closed reduction [3]. The incidence of soft-tissue entrapment is reported in type I injuries as 0%, in type II as 33% and in type III as 65% [5]. Zaricznyj [6] further classified comminuted eminence fractures as type IV [3]. Arthroscopic fixation is now often used for fracture types II–IV, although successful closed reduction traditionally has been employed for type II fractures [3].

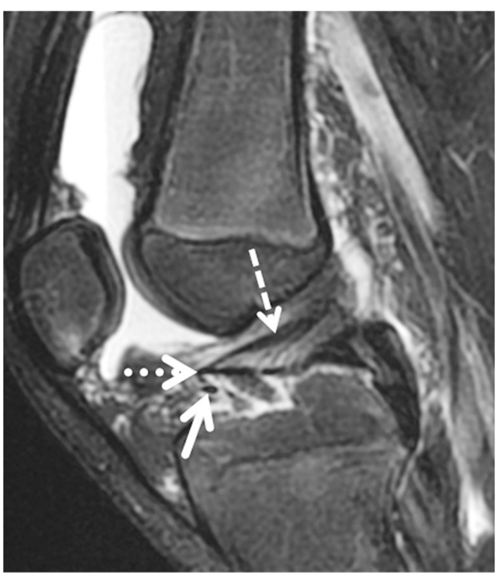

Fig. 2 Intercondylar eminence avulsion in a 10-year-old boy who had a collision during a soccer game. Sagittal fat-saturated T2-W MR image of the right knee shows a posteriorly hinged osteochondral fragment (*dotted arrow*) at the distal ACL attachment (type II intercondylar eminence fracture). The ACL (*dashed arrow*) is intact. The transverse intermeniscal ligament (*solid arrow*) is entrapped beneath the bone fragment. *ACL* anterior cruciate ligament

Although the ACL may appear intact on imaging, residual laxity is often present on clinical examination from partial tearing. However this rarely causes substantial instability or an adverse functional outcome. Few patients ultimately require conventional ACL reconstruction [3, 7, 8], but this remains controversial [9].

Posterior cruciate ligament

Posterior cruciate ligament (PCL) injuries are uncommon in skeletally immature children. When they do occur, however, an osteochondral avulsion fracture is more common than a mid-substance PCL tear [10]. Femoral attachment avulsions of the PCL are reported to be more frequent than tibial avulsions (Fig. 5) in patients with unfused physes [10, 11]. For fractures without substantial displacement, non-operative treatment can be considered. However, in an athletic, skeletally immature individual with a displaced fracture, operative repair might offer earlier return to sports and prevent subsequent meniscal tears, articular cartilage degeneration and quadriceps atrophy, all of which have been reported in adults [10, 11].

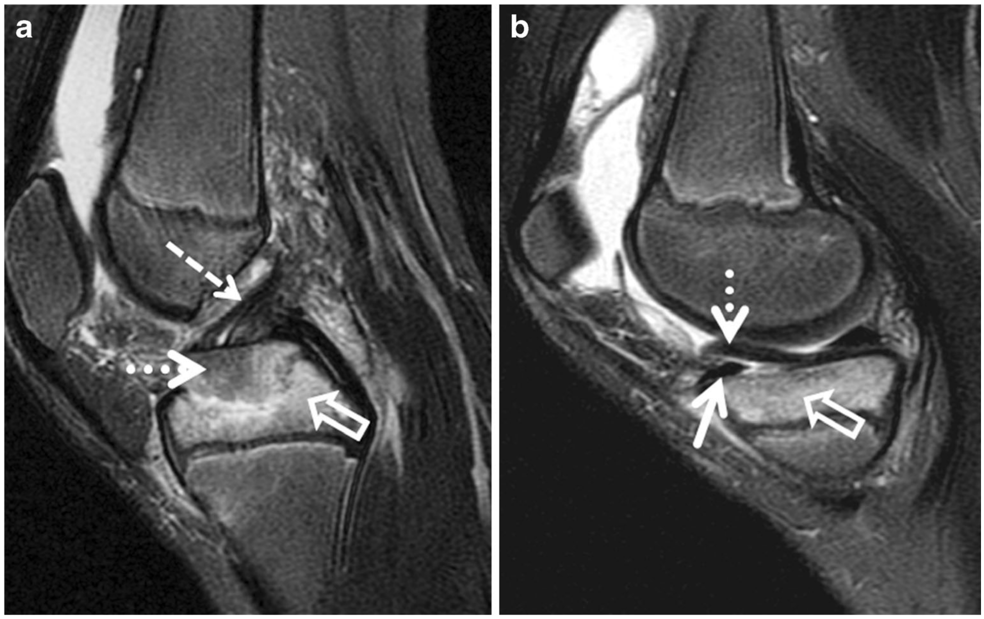

Fig. 3 Type III intercondylar eminence avulsion in an 11-year-old boy with a basketball injury. **a** Sagittal fat-saturated T2-W MRI of the right knee shows displacement of a large osteochondral bone fragment (*dotted arrow*) from the tibial epiphysis at the distal ACL attachment. The ACL (*dashed arrow*) is intact. **b** A slightly more medial image shows the anterior horn of the medial meniscus (*solid arrow*) entrapped between the osteochondral fragment (*dotted arrow*) and donor site. Poorly defined increased fluid-signal intensity, representing marrow edema or hemorrhage, is seen in the adjacent tibial epiphysis (*open arrows* in **a, b**). *ACL* anterior cruciate ligament

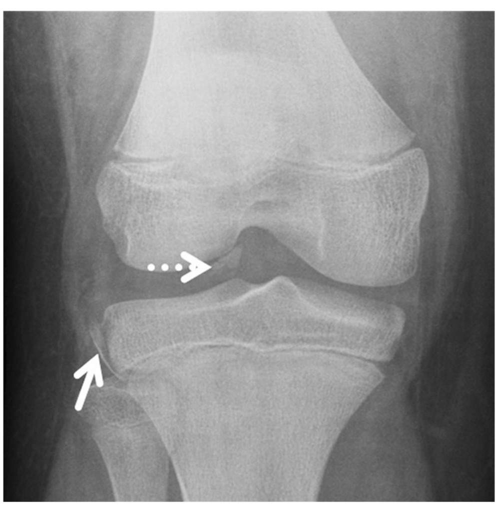

Fig. 4 Intercondylar eminence and Segond avulsion fractures in a 9-year-old girl injured in a dirt bike accident. Anteroposterior radiograph of the right knee shows a vertically oriented fragment (*solid arrow*) along the lateral aspect of the proximal tibial epiphysis, typical of a Segond fracture. An additional irregular bone fragment (*dotted arrow*) is seen superior to the lateral tibial spine, consistent with a concomitant ACL avulsion from the tibial intercondylar eminence. *ACL* anterior cruciate ligament

Avulsion fractures of the lateral compartment

Iliotibial band

Avulsion of a fragment from the anterolateral tibial epiphysis (Gerdy tubercle, Fig. 6) results from an acute tensile stress on the iliotibial band. It occurs most commonly with isolated varus insults and is frequently associated with concomitant ACL injuries [1]. An avulsion fracture of the Gerdy tubercle detected on radiographs has been suggested as an indirect sign of an ACL injury [12].

Fibular/lateral collateral ligament and popliteus tendon

Avulsion fractures related to the popliteus tendon, lateral collateral ligament and popliteofibular ligament are rare. Although these injuries are associated with cruciate ligament tears in adults, they can be seen as isolated findings in skeletally immature patients [13]. Isolated avulsion of the popliteus tendon (Fig. 7) has been reported in children [14] but also occurs with simultaneous avulsion of the fibular collateral ligament (Fig. 8). This latter injury is more severe, referred to as the peel-off complex of posterolateral corner injuries [15]. This association is not surprising given that the proximal attachment of the fibular collateral ligament to

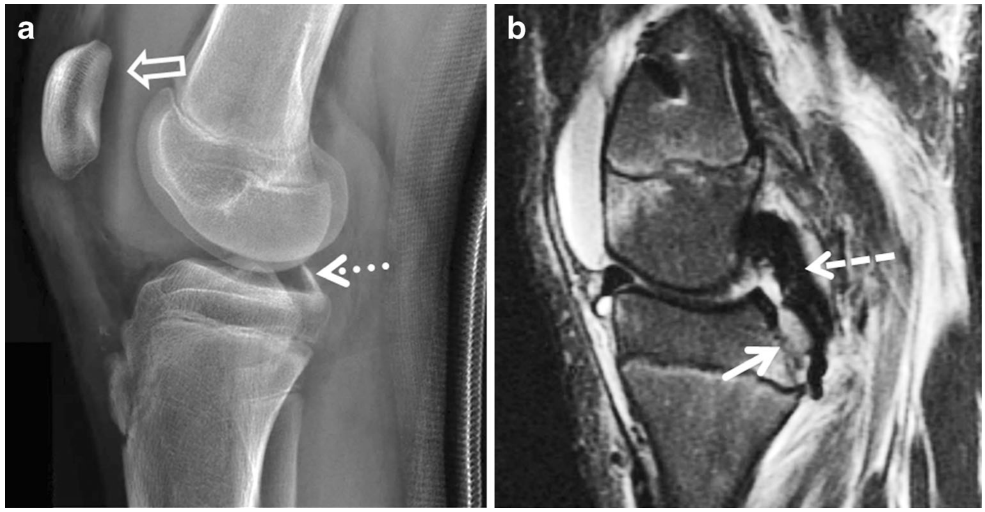

Fig. 5 Posterior cruciate ligament (PCL) avulsion. **a** Cross-table lateral radiograph shows an obliquely oriented linear fragment (*dotted arrow*) over the posterior portion of the knee joint. A layering fat-fluid level (*open arrow*) is seen within the joint space, consistent with a lipohemarthrosis and confirming an intra-articular fracture. **b** Sagittal fat-saturated T2-W MRI shows avulsion of the PCL (*dashed arrow*) at its distal tibial attachment (*solid arrow*). Images courtesy of Dr. Hank Baskin

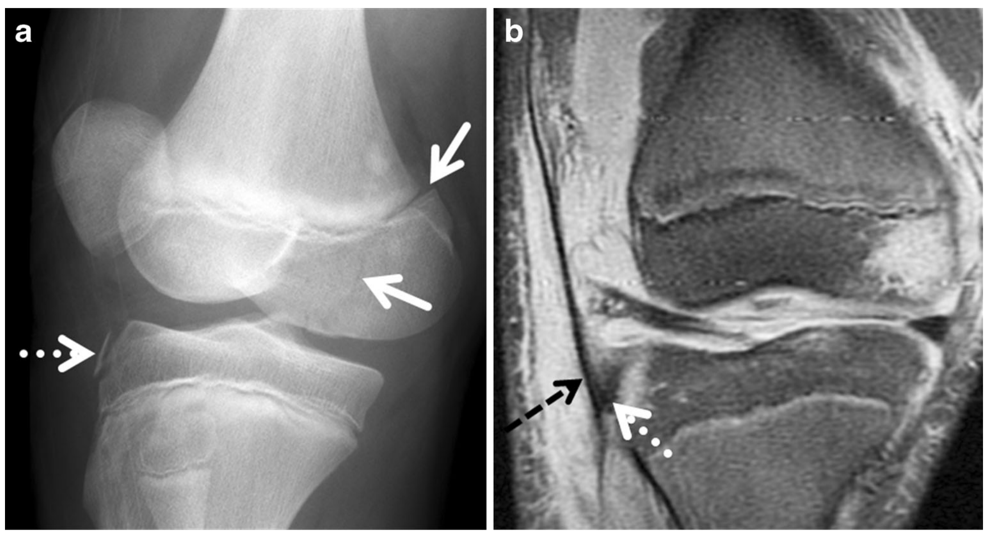

Fig. 6 Iliotibial band avulsion in a 13-year-old boy who was hit by a car. **a** External oblique radiograph and (**b**) coronal fat-saturated proton-density-W MRI show a vertically oriented linear bone fragment (*dotted arrows*) displaced from the anterolateral aspect of the proximal tibial epiphysis at the attachment site of the iliotibial band (*dashed arrow* in **b**). A Salter–Harris III fracture (*solid arrows* in **a**) is also seen at the distal femoral physis and epiphysis

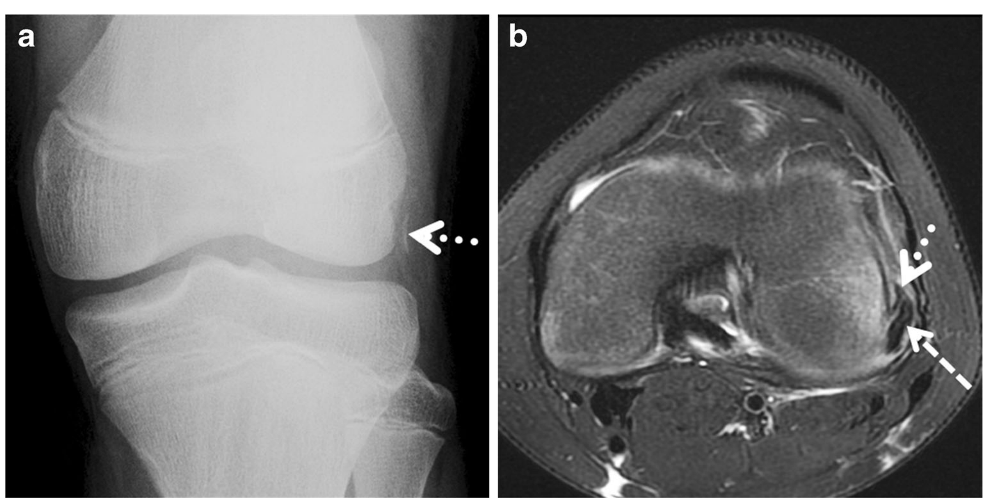

Fig. 7 Popliteus tendon avulsion in a 13-year-old boy injured during a snowboarding accident. **a** Anteroposterior radiograph and (**b**) axial fat-saturated T2-W MRI of the left knee show a vertically oriented linear fragment (*dotted arrows*) along the distal aspect of the lateral femoral condyle. The origin of the popliteus tendon (*dashed arrow* in **b**) is attached to this fragment

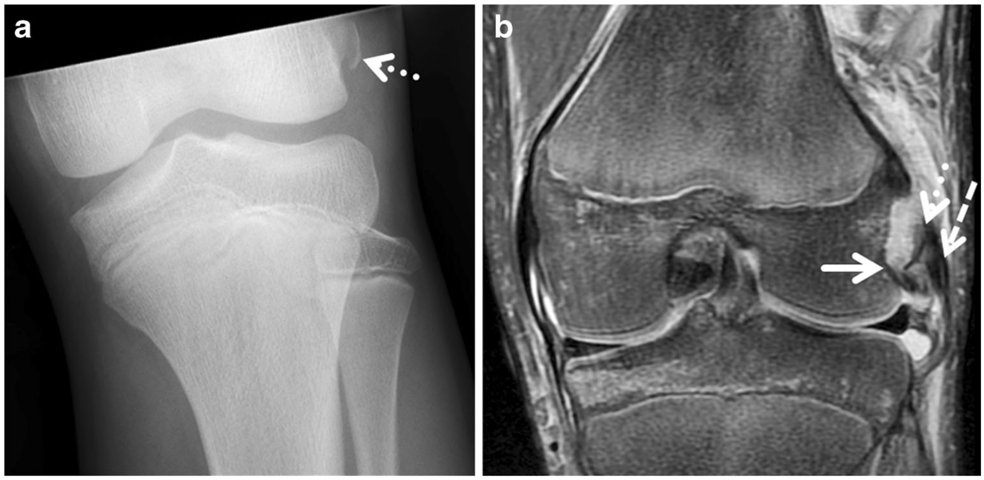

Fig. 8 Fibular collateral ligament avulsion in a 13-year-old boy who was hit by a car. **a** Anteroposterior radiograph and (**b**) coronal fat-saturated T2-W MRI show an osseous fragment (*dotted arrows*) that has been avulsed from the mid-portion of the lateral femoral condyle at the proximal attachment site of the fibular collateral ligament (*dashed arrow* in **b**). A portion of the popliteus tendon origin, inferior to the fibular collateral ligament attachment, has also been avulsed from the femur, with an intact popliteus remnant noted (*solid arrow* in **b**)

the lateral epicondyle lies just superior to the origin of the popliteus tendon along the superior aspect of the lateral notch or groove between the epicondyle and the lateral condylar articular surface.

A popliteus tendon and fibular collateral ligament avulsion injury has been reported in one conservatively managed case to cause growth disturbance and severe valgus deformity requiring a wedge osteotomy [13]. This deformity might reflect the proximity of the fibular collateral ligament attachment to the distal femoral physis. This is in contradistinction to the majority of other cases in that same series which initially were managed operatively and developed no growth disturbance [13]. As such, open reduction and fixation may yield an improved outcome.

Arcuate ligament and conjoined tendon

The fibular styloid process is the site of attachment of the arcuate complex, which includes the arcuate, fabellofibular (when present) and popliteofibular ligaments [16]. Anterior and inferior to the attachment of the arcuate complex, the fibular collateral ligament and biceps femoris tendon attach as a conjoined structure on the lateral aspect of the proximal fibular epiphysis [17]. These structures provide much of the posterolateral stabilization of the knee joint.

The "arcuate sign" refers to a horizontally oriented avulsion fracture fragment (Fig. 9) at the attachment of the arcuate complex. This injury can lead to posterolateral instability and is highly associated with cruciate ligament, medial collateral ligament and meniscal injuries [1, 16]. In addition, isolated avulsion injuries of the arcuate complex can occur with minor trauma, go unrecognized clinically, and thus lead to chronic instability. High failure rates of ACL and PCL reconstructions have been attributed to lack of recognition of concomitant posterolateral corner injury [1].

Lateral capsular ligament

Another avulsion fracture about the knee indirectly related to ACL injuries is the Segond fracture (Fig. 4), which consists of a vertically oriented bone fragment along the lateral tibial epiphysis and has a high association with ACL injuries [1]. The Segond fracture is classically described at the attachment site of the lateral capsular ligament; however, the posterior iliotibial band and the fibular collateral ligament oblique band can also be contributory [1].

Fig. 9 Arcuate complex avulsion in a 14-year-old girl who was struck by a car. Lateral radiograph of the knee shows a horizontally oriented sliver of bone (*dashed arrow*) that has avulsed from the fibular epiphysis

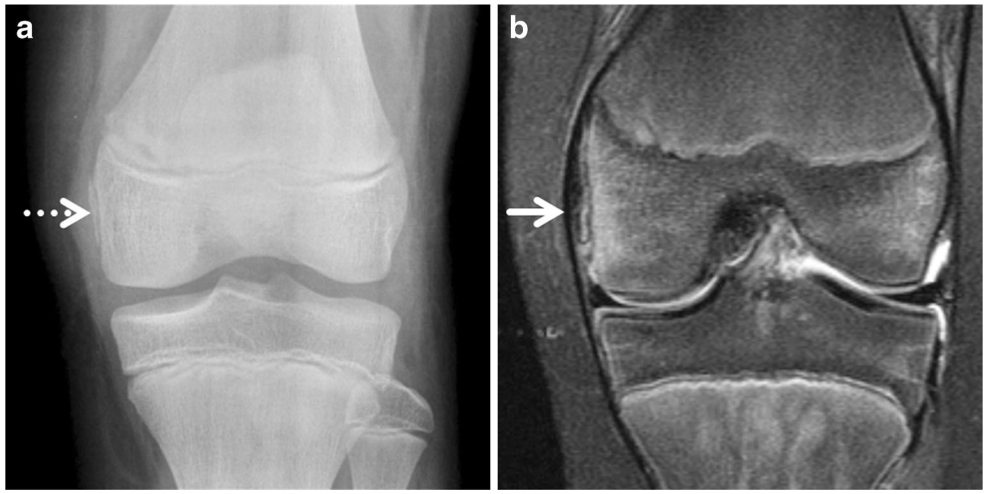

Fig. 10 Medial collateral ligament (MCL) avulsion in a 12-year-old boy injured in a dirt bike accident. **a** Anteroposterior radiograph and (**b**) coronal fat-saturated T2-W MRI of the left knee show a vertically oriented linear fragment (*dotted arrow*) along the midportion of the medial femoral condyle. The deep meniscofemoral portion of the MCL (*solid arrow*) is primarily associated with this fragment

Avulsion fractures of the medial compartment

Medial collateral ligament

Avulsion fractures at the proximal attachment of the medial collateral ligament (MCL) on the distal femur are very rare injuries in children (Fig. 10). Femoral attachment MCL avulsions primarily have been reported at the deep rather than superficial MCL fibers in adults [18]. Interestingly, the femoral attachment of the MCL remains distal to the femoral physis with virtually no change in position throughout skeletal growth [19]. Therefore if repair of an avulsed proximal MCL is contemplated in a young patient, no adjustment for degree of skeletal maturation is necessary. Intra-articularentrapment of avulsed distal MCL fibers has been reported in a child [20].

Meniscotibial ligament

A reverse Segond fracture can occur along the medial proximal tibial margin at the distal attachment of the deep medial collateral ligament (MCL) fibers (also known as the meniscotibial or coronary ligament). This fracture is associated with mid-substance PCL tears as well as avulsions of the PCL from the posterior tibial plateau [1].

Avulsion fractures of the extensor mechanism/retinaculum

Medial patellofemoral ligament

The patellar dislocation–relocation injury is one of the most common injuries to affect the pediatric knee. Lateral dislocation of the patella typically is transient, but the patella rarely remains dislocated at the time of initial imaging (Fig. 11) [21]. Upon relocation, frontal and lateral radiographs sometimes show only soft-tissue swelling and joint effusion. However a fracture can occur at the medial border of the patella as a result of avulsion of the patellar attachment of the medial patellofemoral ligament. Such fragments are best seen on an axial or tangential view (such as the sunrise or Merchant view) of the patellofemoral joint (Fig. 12) [21].

The typical lateral direction of patellar movement in dislocation injuries usually results in poorly circumscribed foci of high T2 signal intensity in the bone marrow of the medial patella and lateral femoral condyle, which reflects edema or hemorrhage related to trabecular microfracture or true impaction fracture. This pattern of marrow signal abnormalities is termed “kissing contusions” [21].

Articular cartilage injuries occur frequently and are seen in up to 95% of patellar dislocations during arthroscopy [22].

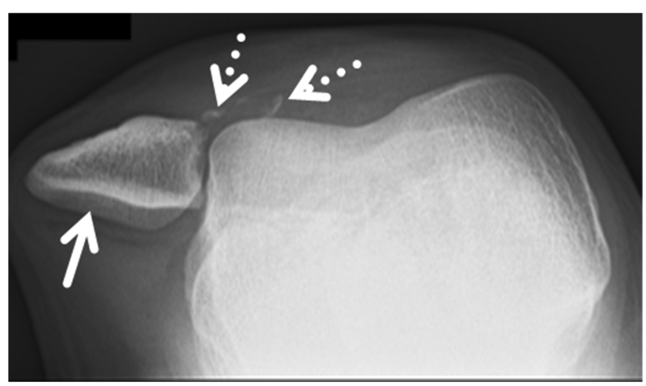

Fig. 11 Patellar dislocation with medial patellofemoral ligament avulsion in a 14-year-old girl with a soccer injury. Radiograph axial to the patellofemoral joint shows persistent lateral dislocation of the patella (*solid arrow*). Numerous bony fragments (*dotted arrows*) lie anterior to the lateral femoral condyle, indicating medial patellofemoral ligament avulsion injury

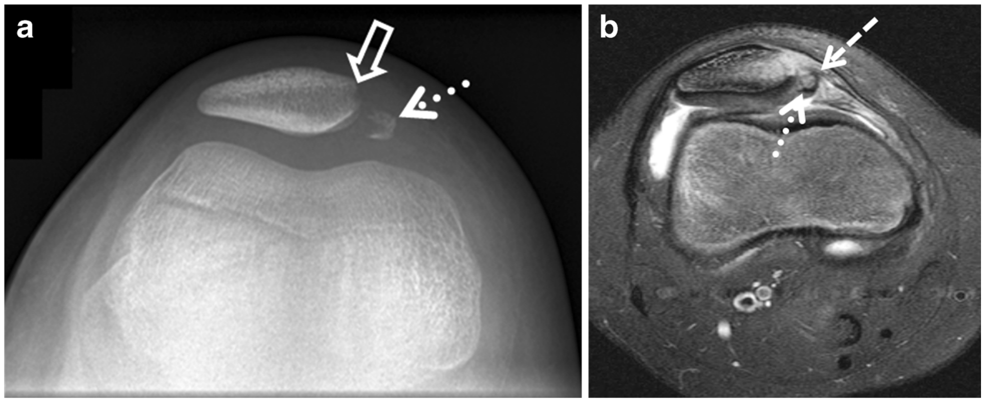

Fig. 12 Patellar dislocation with medial patellofemoral ligament avulsion in a 10-year-old girl. **a** Radiograph axial to the patellofemoral joint and (**b**) axial fat-saturated T2-W MRI of the right knee show an irregular ossific fragment (*dotted arrows*) along the medial aspect of the patella. The donor site of the medial patella also has an irregular contour (*open arrow* in **a**). The medial patellofemoral ligament attachment at this level is thickened with increased fluid signal intensity (*dashed arrow* in **b**), which could be reactive or caused by a partial tear

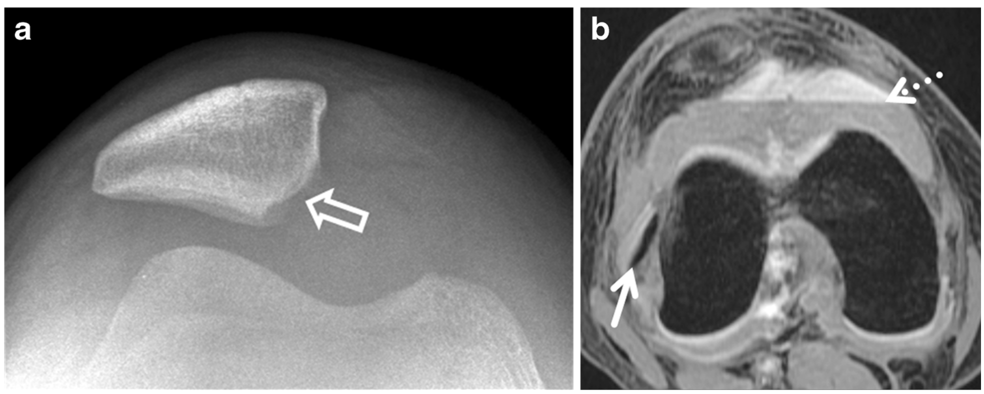

Fig. 13 Transient patellar dislocation in an 11-year-old girl with a basketball injury. **a** Radiograph axial to the patellofemoral joint and (**b**) axial fat-saturated gradient recalled echo MRI of the left knee. The patella is laterally subluxed with focal loss of bone centrally (*open arrow* in **a**), which is not in the expected location for an avulsed medial patellofemoral ligament fragment. A large osteochondral fragment lies within the lateral gutter (*solid arrow* in **b**), consistent with an intra-articular body that originated from the patella during a transient patellar dislocation. The layering fluid level (*dotted arrow* in **b**) is typical of a hemarthrosis

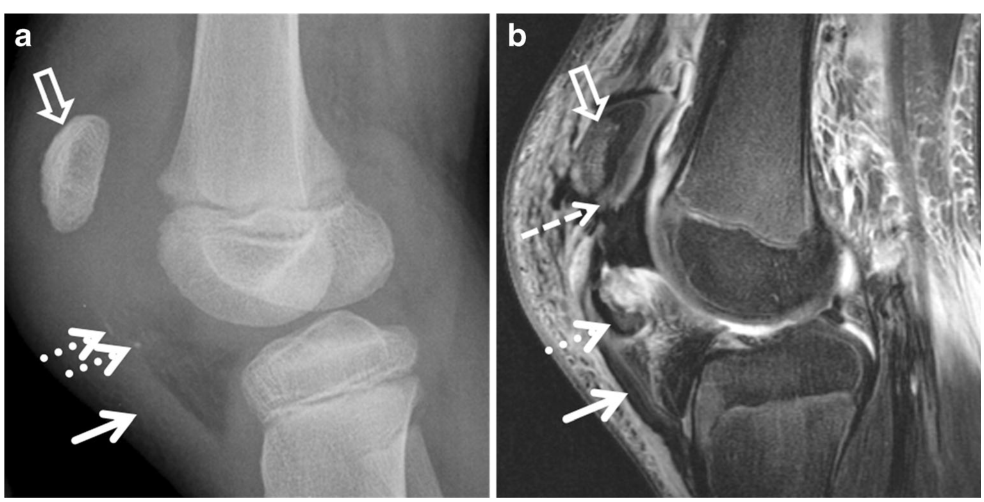

Fig. 14 Patellar sleeve fracture in a 10-year-old boy with a football injury. **a** Lateral radiograph and (**b**) sagittal fat-saturated T2-W MRI show elevation of the patella (*open arrows*) with marked soft-tissue edema and a hemorrhagic joint effusion. Tiny ossific fragments (*dotted arrows* in **a**) lie along the superior aspect of the redundant patellar tendon (*solid arrows*). There is a large sleeve of unossified cartilage at the level of the bony fragments (*dotted arrow* in **b**) with corresponding interruption of the residual unossified cartilage surrounding the patella (*dashed arrow* in **b**)

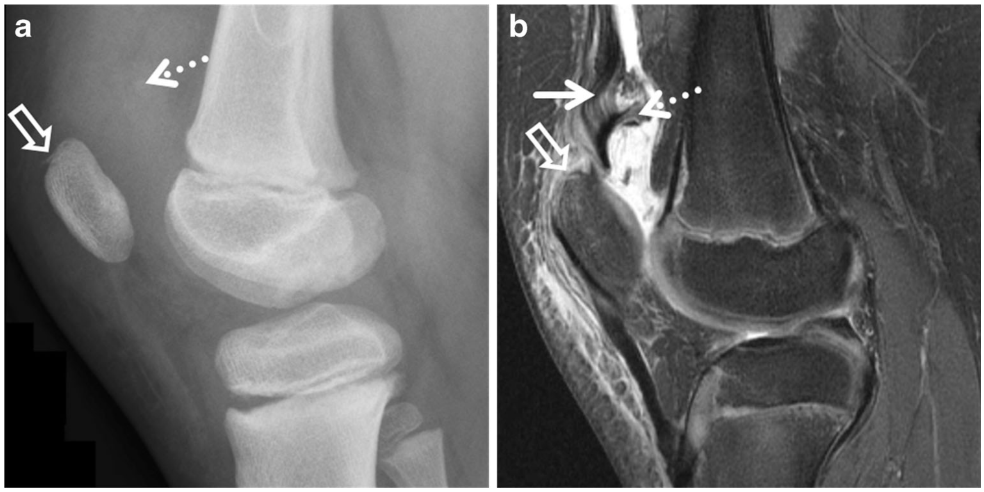

Fig. 15 Patellar sleeve fracture in a 9-year-old boy who hit his knee against a diving board. **a** Lateral radiograph and (**b**) sagittal fat-saturated T2-W MRI show mild bony irregularity of the patellar superior pole (*open arrow* in **a**) with interruption of the unossified patellar cartilage at this level on MRI (*open arrow* in **b**). A tiny ossific fragment lies posterior and superior to the patella (*dotted arrow* in **a**) with a large joint effusion and overlying soft-tissue swelling. MRI reveals avulsion of a larger sleeve of patellar cartilage (*dotted arrow* in **b**), which is retracted by a lax quadriceps tendon (*solid arrow* in **b**)

These range from articular surface cracks (i.e. lower-grade injuries such as fissures) to larger focal cartilaginous or osteocartilaginous defects (Fig. 13). When these larger defects are identified, careful analysis of the entire joint space is required to look for free osteochondral fragments that must be repaired or removed. The cartilage of the medial patellar facet is more frequently injured than that of the lateral femoral condyle, and this injury classically occurs with impaction and/or shearing during the patellar relocation movement [22].

Patellar sleeve

Fractures that occur at the inferior and, less frequently, superior poles of the pediatric patella typically are sleeve-type avulsion injuries, so named because of the relatively large sleeve of unossified patellar cartilage that accompanies the small bony fragments. These avulsion injuries occur at the attachment sites of the patellar or quadriceps tendons, respectively (Figs. 14 and 15). Assessment for patellar alignment (alta or baja), location of soft-tissue swelling and ossific fragments, and joint effusion will provide radiographic clues to this diagnosis. These fractures most frequently occur when there is resistance against a forceful quadriceps contraction, such as with knee flexion during athletic activity. Operative fixation is typically required if the patellar articular cartilage is involved by the fracture, with the goal of preventing premature joint degeneration [23, 24]. An appropriate history of an acute event without previous pain helps to differentiate a minimally displaced patellar sleeve avulsion from the chronic avulsion changes of Sinding–Larsen–Johansson disease.

Tibial tubercle

Tibial tubercle avulsions typically occur in boys age 13–17 years. Until just prior to physeal fusion, the portion of the proximal tibial physis deep to the ossifying tibial tubercle apophysis is uniquely composed of fibrocartilage rather than hyaline cartilage. Close to the time of physeal fusion, this segment of fibrocartilage is replaced by weaker hyaline cartilage, which subsequently predisposes the tibial tubercle to avulsion fractures that involve the physis (Salter–Harris

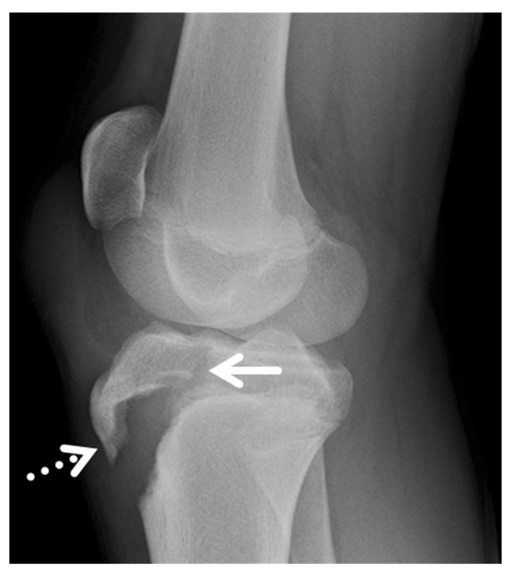

Fig. 16 Tibial tubercle avulsion in a 15-year-old boy with a soccer injury. Lateral radiograph shows an osseous avulsion of the tibial tubercle (*dotted arrow*) that extends proximally through the epiphysis (*solid arrow*) to the articular surface, consistent with a Salter–Harris III fracture

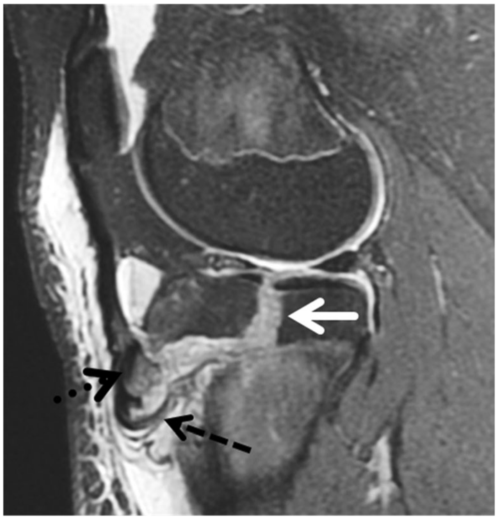

Fig. 17 Tibial tubercle avulsion in a 15-year-old boy who fell while getting onto a school bus. Sagittal fat-saturated T2-W MRI shows the avulsed fracture fragment (*dotted arrow*) at the patellar tendon insertion. There is proximal physeal and epiphyseal extension (*solid arrow*) of the fracture to the articular surface. The tibial periosteum (*dashed arrow*), which is continuous with the distal patellar tendon insertion, has been stripped from the proximal tibia and is trapped within the fracture

injuries) [21, 25, 26]. Patients with prior Osgood–Schlatter disease (i.e. chronic repetitive avulsion injury at the site of patellar tendon insertion, which occurs at an earlier stage of tubercle ossification) may be at increased risk for tibial tubercle avulsion injuries [21]. Classic histories for tibial tubercle fractures include quadriceps contraction with extension (e.g., jumping) and rapid flexion against a contracted quadriceps (e.g., landing) [21, 26].

Fractures of the tibial tubercle should be evaluated radiographically for the degree of comminution and displacement as well as for the pattern of extension. When the fracture plane extends proximally through the tibial physis into the adjacent metaphysis (usually posteriorly), it is considered a Salter–Harris type II injury. If the fracture plane extends into the proximal tibial epiphysis (typically to the articular surface), it results in a Salter–Harris type III pattern (Figs. 16, 17 and 18). Salter–Harris type IV fractures with both metaphyseal and epiphyseal extension have rarely been described at this site [26].

Other than small, mildly displaced fractures limited to the anterior tibial tubercle ossification center, most tibial tubercle avulsions undergo operative fixation to restore alignment of the extensor mechanism and congruency of the tibial articular surface [26]. Specific imaging features with operative implications include the presence of substantial tubercle displacement, Salter–Harris physeal extension, >2 mmtibial articular surface step-off, and entrapment of adjacent tissue preventing adequate closed reduction. Concomitant injuries to other segments of the extensor mechanism have also been reported, including tears of the patellar and quadriceps tendons requiring repair [25].

Similar to avulsive patellar injuries, an appropriate history of an acute event without previous pain helps to differentiate radiographic findings of minimally displaced tibial tubercle avulsions (not shown) from the chronic avulsion changes of Osgood–Schlatter disease.

Conclusion

Familiarity with radiographically apparent avulsion fractures of the pediatric knee can predict associated soft-tissue injuries and help direct patient management. A careful imaging evaluation must be performed for possible accompanying injuries, such as intra-articular fracture extension, intra-articular loose bodies, and entrapped soft-tissue structures, each of which can alter therapy.

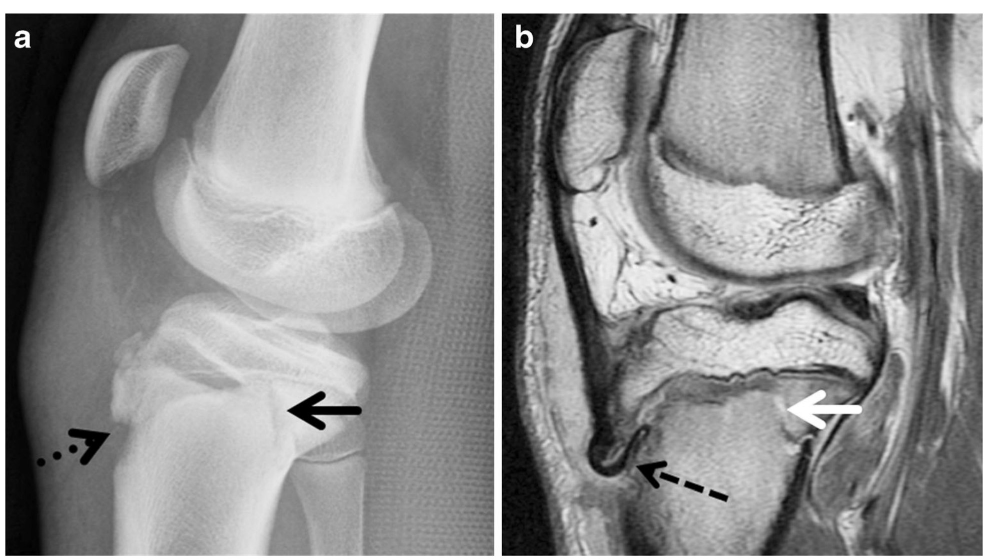

Fig. 18 Tibial tubercle avulsion. **a** Lateral radiograph and (**b**) sagittal proton-density MRI show a tiny fracture fragment at the inferior tibial tubercle (*dotted arrow* in **a**) with stripped proximal tibial periosteum (*dashed arrow* in **b**) interposed between fracture components. The fracture extends proximally through the tibial physis before exiting the posterior metaphysis (*solid arrows*) as a Salter–Harris II fracture

Conflict of interest None

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