31 Lower Extremity Injuries in Adults and Children: Evidence-Based Emergency Imaging

Sarah D. Bixby and Stefan Puig

Key Points

- Radiography is the initial imaging strategy in a child or adult with lower extremity injury in the emergency department (ED) setting (strong evidence).
- However, many emergent radiographs can be omitted without missing a clinically significant fracture when well-validated clinical decision rules, such as the Ottawa knee and ankle rules in children and adults, are followed (strong evidence).
- Noncontrast computed tomography (CT) is infrequently indicated for further characterization of fracture patterns that may require surgical fixation or in severely injured patients in need of a rapid diagnostic work-up (moderate evidence).
- Magnetic resonance imaging (MRI) is much more sensitive for diagnosis and characterization of soft tissue injury and radiographically occult fractures, though the decision to proceed to MRI depends upon location of injury and findings on initial radiographs (strong evidence).

S.D. Bixby (✉)
Department of Radiology, Boston Children's Hospital, Boston, MA, USA
e-mail: Sarah.bixby@childrens.harvard.edu

S. Puig
Department of Diagnostic, Interventional, and Pediatric Radiology, Inselspital, University Hospital Bern, University of Bern, Bern, Switzerland

Department of Radiology and Neuroradiology, Klinik im Park, Hirslanden AG, Zurich, Switzerland
e-mail: Puig1@mac.com

Definitions and Pathophysiology

This chapter focuses on imaging the child, adolescent, and adult presenting with lower extremity trauma from the hip to the toe, with specific attention on conditions that require imaging, as well as the most accepted imaging approach. Lower extremity injuries are common in patients of all ages, particularly in children who are active and involved in activities that place stress on their growing bones. Overuse injuries are far more common in the older child, adolescent, and young adult involved in organized athletic activities, particularly high-impact activities. Pediatric patients are at greater risk of overuse injuries compared to their adult counterparts because growing bones are relatively weak, particularly when the growth plates are unfused [1]. There are a number of lower extremity injuries that are unique to children, which vary depending on the age of the patient and the mecha-

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nism of injury. Since there are not (yet) enough studies to support specific imaging recommendations of lower extremity injuries in pediatric patients, this chapter will describe pediatric injuries in more detail while it will discuss injuries affecting adults and older children, for which evidence-based imaging guidelines are available, only briefly.

Epidemiology

Lower extremity injuries have a high incidence and place a major burden on health care. A data analysis of the US National Electronic Injury Surveillance System gave insight into the distribution of lower extremity injuries in patients presenting to US EDs [2]: The most common area of injury is the lower trunk (28%), followed by the ankle (20%), knee (16%), foot (15%), lower leg (11%), toe (7%), and upper leg (4%). Strains and sprains account for 36% of all lower extremity injuries followed by contusions/abrasions (19%), fractures (18%), and lacerations (8%). Fractures are the most common injuries to the toe, lower leg, and upper leg. Strains or sprains are the most common injuries in the ankle, the knee, and the lower trunk. Younger patients are more likely to have ankle sprains, foot contusions/abrasions, and foot strains/sprains. Older patients are more likely to have lower trunk fractures and lower trunk contusions/abrasions.

Overall Cost to Society

Injuries are a major cause of total health-care costs in the industrialized world. An analysis of hospital discharge registers of ten European countries was used to estimate injury incidence and costs per capita by sex, age, and type of injury [3]. The patterns of costs by these criteria were quite similar between countries. Costs per capita increase exponentially in older age groups, due to the combined effect of high incidence and high costs per patient. Elderly women, young children, and male adolescents are high-cost groups. In lower extremity injuries, the highest costs arise for fractures of the hip, pelvis, and femur shaft (mean, 5530 € or $6083), followed by complex soft tissue injury (mean, 3535 € or $3889), fracture of the knee or lower leg (mean, 3504 € or $3854), and ankle fractures (2636 € or $2900). This cost distribution may be similar for the USA with higher mean costs per injury because of the more expensive health-care system as compared to Europe. Fractures of the hip, pelvis, or femur shaft also raise the highest cost per capita of all types of injuries and other locations than the lower extremities.

Goals of Imaging

The primary goal of imaging in patients presenting after lower extremity trauma is to identify fractures that require immediate immobilization and/or identify other explanations for pain and disability. The ultimate goal of imaging is to assist clinicians with appropriate treatment strategies to allow the patient to ultimately return to normal activities and avoid untoward complications.

Methodology

A Medline search (US National Library of Medicine database) for original articles published between 1966 and 2015 using Ovid and PubMed search engines was performed using different key search terms including *(pediatric) lower extremity trauma, imaging (pediatric) knee injury, imaging (pediatric) hip injury, imaging (pediatric) ankle injury, imaging (pediatric) foot injury, imaging (pediatric) fractures, (pediatric) lower extremity imaging, (pediatric) osteochondral lesions, traumatic hip dislocation, imaging slipped capital femoral epiphysis, pelvic avulsion fracture, femoral neck fracture imaging, physeal fractures, traumatic patellar dislocation, Ottawa ankle rules (children),* and *Ottawa knee rules (children)*. The search was limited to human studies written in English. Abstracts were reviewed and selected based on applicability of the subject matter and the overall methodology. Additional articles were reviewed and selected based on the references of the reviewed articles.

Discussion of Issues

Which Imaging Modalities Are Used in the Initial Evaluation of Lower Extremity Injury?

Summary of Evidence There is strong evidence to support the use of radiographs in the evaluation of lower extremity trauma. While CT is not routinely used to evaluate fractures, it may be helpful to surgeons for presurgical planning and management (moderate evidence). MRI is considered on a case-by-case basis depending on the area of concern (strong evidence). While there are settings in which ultrasound may be useful, ultrasound is operator dependent, and there is little data supporting its routine use in the imaging evaluation of injured patients (limited evidence).

Table 31.1 Suggested radiographic views for both children and adults of lower extremities after trauma

Body part	Standard views
Hip	Anteroposterior and cross-table or frog-leg lateral of affected hip
Femur	Anteroposterior and lateral
Knee	Anteroposterior and lateral[a]
Tibia and fibula	Anteroposterior and lateral
Ankle	Anteroposterior, oblique (ankle mortise), and lateral
Foot	Anteroposterior, oblique, and lateral
Calcaneus	Harris-Beath (axial) and lateral

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[a]Both oblique view and sunrise (skyline) view may be added when a tibial plateau fracture or a patellar fracture, respectively, is suspected

Supporting Evidence

Radiography

With few exceptions, the initial imaging strategy for a patient with concern for lower extremity trauma is radiography [4–7]. Despite widespread availability of more advanced imaging such as computed tomography (CT) and magnetic resonance imaging (MRI), radiographs remain the first-line imaging tool for detection of fractures. Standard radiographic views are acquired in two orthogonal planes. Additional views may be indicated depending on the anatomic area and the clinical concern (Table 31.1). In pediatric patients, comparison views of the unaffected limb are not routinely helpful if the initial interpretation is from a pediatric radiologist [8]. In some specific fractures, additional cross-sectional imaging may be necessary to determine an appropriate management plan. In the setting of normal radiographs, cross-sectional imaging may be warranted to evaluate for subtle fractures or soft tissue injuries that are not visible on radiographs. Radiographic approaches to specific injuries will be described in the various subsections.

Computed Tomography

Computed tomography may be useful in patients with displaced or complex fractures for a more thorough evaluation of the fracture pattern and degree of displacement of fracture fragments [4–7]. Computed tomography may also be useful when a fracture through a pathologic lesion is suspected, to better characterize the lesion. CT is most often reserved for patients for whom surgical management is deemed likely. The multiplanar and 3D imaging capabilities of CT allow surgeons to better understand the fracture pattern before deciding upon the most appropriate treatment strategy [9–12]. Computed tomography is otherwise not indicated in routine characterization of fracture patterns.

Magnetic Resonance Imaging

Magnetic resonance imaging is useful for identifying fractures that have no radiographic abnormality as well as ruling out other pathologies [4–7, 13]. The knee and the ankle are two of the most commonly injured joints [14]. While MRI findings in the knee often result in a change in diagnosis that carries treatment implications for the patient, MRI findings in the ankle rarely lead to a substantive change in therapeutic management [14]. Magnetic resonance imaging is therefore most useful for evaluation of knee injuries that are concerning for ligamentous injury or internal derangement or as a problem-solving tool when radiographs fail to identify a source of pain in a patient with persistent pain after trauma, such as stress fractures or muscle injury.

Ultrasound

Though there are reports that ultrasound (US) has the ability to detect occult fractures in pediatric patients [15, 16], the use of US is not routine in the immediate work-up of a child with concern for lower extremity fracture. There are some indications for which US may be useful in conjunction with other imaging. Ultrasound is an excellent means of assessing for joint effusion, particularly within the hip where radiographs are insensitive [17]. Ultrasound is also useful for evaluating peripheral vascular injuries in the lower extremity [18]. It also plays a unique role in the imaging of neonates with concern for fracture, given that the epiphyses of the long bones are unossified [19]. It is also helpful in the detection of soft tissue injuries such as muscle hernias [20] and intramuscular hematomas [21]. Dynamic US is also useful in evaluating tendon dysfunction and tendon tear [22, 23]. Given that this chapter primarily focuses on evaluating for osseous injury after trauma, US will not figure prominently into the subsequent discussions despite the excellent capability of ultrasound to evaluate for soft tissue injury.

What Is the Imaging Approach to Hip Injury?

Summary of Evidence There are no strict or specific imaging recommendations for the pediatric hip in the setting of an acute injury (limited evidence). The decision to image, and which imaging modalities are most effective, will depend on clinical history and symptoms. In middle-aged and elderly patients presenting with acute hip pain, radiography is the established initial imaging tool, although its diagnostic accuracy is not very high (strong evidence). MRI is the most appropriate modality to use in patients with radiographically indeterminate findings (strong evidence). Head-to-head comparisons of CT and MRI showed the superiority of MRI in the evaluation of hip injury (moderate evidence). Bone scintigraphy and US play a minor or no role, respectively, in hip injury of adults (limited evidence).

Supporting Evidence

Pediatric Hip Injuries

Pelvic avulsion fractures occur in the active adolescent population, particularly those engaged in high-intensity sporting activities. In skeletally immature patients, the pelvic apophyses serve as attachment site of major tendons. Apophyses are secondary growth centers with a physeal equivalent, which renders them inherently weaker than the adjacent bone. Pelvic avulsion injuries may occur at different sites [24]. Apophyseal avulsions occur prior to physeal closure and are caused by forceful contraction of the attaching muscles. An anteroposterior (AP) radiograph of the pelvis is sufficient in the initial evaluation of most avulsion fractures, with an additional oblique view when an anterior inferior iliac spine (AIIS) (straight head of the rectus femoris) fracture is suspected [25]. The fractures may be recognized on radiographs by the displacement of an ossified apophyseal fragment [26, 27]. Magnetic resonance imaging is more sensitive for unossified apophyseal fractures and has the added advantage of detecting other causes of hip pain [28]. Magnetic resonance imaging should be considered if the clinical suspicion for an avulsion fracture is high in the setting of normal radiographs. The degree of displacement of the avulsed apophysis is important, particularly at the ischial apophysis where displacement of greater than 2 cm may result in an unstable fibrous union [29]. As avulsion fractures heal, they become more visible on radiographs as heterotopic new bone forms around the avulsed fragment, oftentimes forming a bridge between the fragment and the pelvis. When repetitive forces are placed on a tendon insertion, a chronic traction apophysitis may result [30]. These injuries are analogous to a nondisplaced Salter 1 fracture and may be undetectable with radiographs in the acute stages. Over time, the osteoblastic healing response leads to increased sclerosis on plain radiographs such that the diagnosis can be made without the need for advanced imaging.

Slipped capital femoral epiphysis (SCFE) is a hip disorder often related to trauma but may also be seen in children with other predisposing factors (e.g., obesity, hypothyroidism). SCFE is the most common physeal injury of the proximal femur. The femoral head is most often displaced posteriorly and medially. Radiographs are the preferred imaging modality [31–34], though early or mild SCFE may have subtle radiographic findings that may be overlooked [34]. Anteroposterior (AP) and frog-leg lateral radiographs are the most recommended views. On the frontal projection, the height of the femoral head is diminished and the physis is widened. The Klein line along the superior margin of the femoral neck may remain normal on the AP view, and therefore a frog-leg view is also recommended [35] where the degree of posterior displacement is best appreciated. When SCFE is suspected clinically but radiographs are not definitive, MRI may be performed for confirmation [36]. Magnetic resonance imaging findings of SCFE include abnormal marrow edema around the physis in addition to physeal widening and/or fluid in the physis [37].

Traumatic posterior dislocation of the hip is an uncommon but serious injury in children resulting from high-impact trauma. Often the femoral head relocates spontaneously shortly after the dislocation event. Imaging of the hips and pelvis is critical in any patient who has sustained high-impact trauma with complaints of hip pain. Initial radiographs should consist of an AP radiograph of the pelvis. If the femoral head remains dislocated on this initial view, reduction of the dislocation should take place before any additional imaging. Imaging clues that suggest that a transient traumatic dislocation event has occurred include nonconcentric position of the femoral head within the acetabulum on radiography or cross-sectional imaging or a posterior wall "fleck" sign (small fragment of bone adjacent to the posterior acetabular rim) on cross-sectional imaging [38]. Radiographs and CT both underestimate the presence of posterior acetabular injury after hip dislocation [39]. Magnetic resonance imaging is more sensitive for detecting bony, cartilaginous, and soft tissue injuries following posterior hip dislocation in children compared to CT [40, 41]. Patients who experience reduction of the femoral head after a traumatic dislocation often have posterior labral avulsion and also suffer posterior wall acetabular fractures and damage to the chondral surface of the femoral head [42].

Fractures of the hip are rare in children and comprise less than 1% of all pediatric fractures [43]. Femoral neck fractures in children are most often the result of high-energy rather than low-energy traumatic events. Although they are rare injuries, they are associated with a high rate of complications, including a 20% risk of osteonecrosis [44]. Radiographs of the child with a suspected femoral neck fracture should include an AP and cross-table lateral radiograph of the hip. An AP view of the entire pelvis may be helpful to evaluate for asymmetry in the proximal femoral physes or to detect subtle fracture lines. When radiographs are normal but a minimally displaced fracture is suspected, cross-sectional imaging is recommended over bone scintigraphy. Magnetic resonance imaging is the most useful imaging test for femoral neck stress fracture with a sensitivity of 100%, versus 68% sensitivity of radionuclide bone scans [45].

Adult Hip Fracture

The initial imaging study for suspected hip fracture in low-energy trauma is radiography. However, Ward et al. list a number of studies showing that radiographs alone cannot reliably exclude fracture in older patients while relevant studies in younger patients are missing [7]. Therefore, in many cases, MRI is needed as follow-up study, also because it reveals the extent and morphology of proximal femoral fractures more accurately [46–48]. Some studies have also shown that MRI is useful in detecting other etiologies for hip pain in patients in which a proximal femur fracture was suspected [49–51].

Although MRI is a costly procedure, it may help to shorten the time to surgery resulting in cost savings, with a systematic review of 52 studies showing that delaying surgery was likely to increase the rate of complications and the length of hospital stay [52].

CT would be able to provide a diagnosis in a more timely manner and has therefore been suggested for the evaluation of radiographically occult hip fractures in patients presenting to the ED after high-energy trauma. The evidence, however, is not (yet) very convincing because the majority of studies comparing CT to MRI results have shown the superiority of MRI in terms of diagnostic accuracy [7].

As far as bone scintigraphy is concerned, Ward et al. list several limitations, such as a higher number of false-positive studies relative to MRI, compromised cardiac and renal function in elderly patients, increased bone turnover related to osteoporosis, and time-consuming procedure [7]. There is a lack of studies and currently, US plays no role for an evidence-based imaging of hip injuries in adults.

What Is the Imaging Approach to Knee Injury?

Summary of Evidence There is strong evidence that the Ottawa knee rules can be applied to children >5 years of age and adults with high sensitivity for detection of significant fractures. Magnetic resonance imaging is more sensitive in the evaluation of certain pediatric knee injuries such as physeal fracture, juvenile osteochondritis dissecans, and lateral patellar dislocation and should be considered on a case-by-case basis on the basis of clinical symptoms and history (moderate evidence). Magnetic resonance imaging is also a valuable and accurate diagnostic tool for the diagnosis of meniscal, cruciate ligamentous, and chondral knee injuries (strong evidence).

Supporting Evidence The Ottawa knee rules (OKR) are a guideline aimed to aid clinicians in determining when radiographs are indicated in the case of knee pain/injury [53]. There are some alternative guidelines available, but the OKR are to date the ones that have undergone the most extensive validation. According to the OKR, radiographs are indicated if a patient is >55 years old, and/or is unable to bear weight immediately and in the ED, and/or has isolated tenderness of the patella, and/or has tenderness at the head of fibula, and/or has inability to flex the knee to 90° [54] (Table 31.2). The reason for the necessity to apply the OKR refers to the fact that only about 5% of patients with acute knee trauma have a fracture on radiographs, while radiographs have been routinely requested in up to 70% [53]. But clinicians should exercise caution in relying solely on a nonsystematic clinical examination, because this may raise the likelihood of missing certain knee injuries, such as fractures of the patella, tibial spine, or fibular head [6].

The OKR can be applied with high sensitivity (92–100%) for children over the age of 5 years and adults, with a 30–40% predicted reduction in radiography rates [6, 55, 56]. One study in particular found that the inability to bear weight was the most sensitive predictor of fracture and would not have missed any fractures in a population of 146 pediatric patients [57]. The proximal tibia was the most common site for fracture in pediatric patients after knee injury, representing 47% of fractures [57]. Below is a discussion of several unique injury patterns in the pediatric knee and their imaging findings.

Specific Pediatric Knee Injuries

Transverse supracondylar fractures are the most common type of distal femur fracture in young children [58]. A supracondylar fracture is a fracture whose center is closer to the knee joint than the width of the femoral condyles and can be diagnosed on the basis of radiographs. These injuries are the result of forced hyperextension after a fall from a height or the result of a direct blow to the leg. Children between 5 and 13 years are most commonly affected [59].

Distal femoral physeal fractures are more common in older children and adolescents. Salter 1 fractures may occur with a sports-related injury in adolescent patients. Magnetic resonance imaging may be helpful for the diagnosis of distal femoral

Table 31.2 Clinical decision rules for radiography of acute knee, ankle, or foot injury

Ottawa knee rule	Ottawa ankle rule: Trauma to the ankle	Ottawa ankle rule: Trauma to the foot
Knee imaging maybe required if[a]	An ankle radiograph series is only required if	A foot radiograph series is only required if
Adult		
Age 55 or older	There is any pain in the malleolar zone	There is any pain in the midfoot zone
Palpable tenderness of head of fibula	And any of the findings below	And any of the findings below
Isolated tenderness of patella (no other bone tenderness)	1. Bone tenderness at the posterior edge or tip of lateral malleolus	1. Bone tenderness over the base of the fifth metatarsal
Inability to flex the knee 90°	2. Bone tenderness at the posterior edge or tip of medial malleolus	2. Bone tenderness over the base of the navicular
Inability to bear weight both immediately and in the ED (four steps, limping is OK)	3. Inability to bear weight both immediately after the injury and in the ED for four steps	3. Inability to bear weight both immediately after the injury and in the ED for four steps
Child		
	There is any pain in the malleolar zone	There is any pain in the midfoot zone
Palpable tenderness of head of fibula	And any of the findings below	And any of the findings below
Isolated tenderness of patella (no other bone tenderness)	1. Bone tenderness at the posterior edge or tip of lateral malleolus	1. Bone tenderness over the base of the fifth metatarsal
Inability to flex the knee 90°	2. Bone tenderness at the posterior edge or tip of medial malleolus	2. Bone tenderness over the base of the navicular
Inability to bear weight both immediately and in the ED (four steps, limping is OK)	3. Inability to bear weight both immediately after the injury and in the ED for four steps	3. Inability to bear weight both immediately after the injury and in the ED for four steps

(continued)

Table 31.2 (continued)

Radiography is indicated if at least one of these characteristics is present [4–6]. These rules apply to both adults and children

[a]If any of the above criteria are met, this patient may need knee imaging: The rule is sensitive to rule out fractures, but not specific to suggest who may have a fracture

physeal fracture when radiographs are equivocal [60, 61]. Salter 2 fractures are more common than Salter 1 fractures of the distal femur, and may be subtle and difficult to detect if there is no fracture displacement, or the metaphyseal fracture line is mistaken for an overlying fat plane. Salter 3, 4, and 5 fractures of the distal femur are much less common and are usually the result of significant force such as motor vehicle collision.

Tibial tubercle fractures usually are sustained as a result of jumping activities with forceful extension or passive flexion against a contracted quadriceps muscle [24]. These injuries may occur prior to the point of fusion of the physis of the tibial tubercle. A defect in the anterior cortex of the tibial tubercle is present, distinguishing this entity from a similar condition, Osgood-Schlatter disease. In the setting of a tibial tubercle fracture, the tubercle may be frankly displaced, or the patellar tendon may be disrupted at its attachment. There are three types of tibial tubercle fracture: Type 1 fractures occur in young adolescents and involve an avulsion of the apophysis without injury to the epiphysis. Type 2 fractures occur in the same age range, but the fracture extends slightly into the epiphysis, which is slightly lifted. Type 3 fractures occur in older adolescents and include a fracture through the epiphysis into the joint [24].

While adults and older adolescents are prone to mid-substance tears of the anterior cruciate ligament (ACL), younger children who are still actively growing are more likely to avulse the tibial eminence at the attachment site of the ACL than to rupture the ACL itself. There are three types of *tibial eminence fractures* based on the degree of displacement of the fracture fragment into the joint space: Type 1 fractures are nondisplaced, type 2 fractures demonstrate elevation of the anterior fragment and no displacement posteriorly (a hinged fragment), and type 3 fractures are displaced in their entirety [62].

Also termed "osteochondral defect," *juvenile osteochondritis dissecans* (OCD) is characterized by abnormalities within the subchondral bone and overlying articular cartilage at focal areas within the knee. OCDs are a common cause for knee pain in young patients who may present at the ED. These lesions are characterized by alterations in the subchondral bone and articular cartilage along the femoral condyles, patella, or trochlear groove of the distal femur and may be considered either stable or unstable by virtue of the status of the overlying cartilage and the presence of fluid undermining the lesion at MRI [63]. The medial femoral condyle is the most common site of involvement followed by lateral femoral condyle, patella, and trochlea [64]. The cartilage overlying the lesion may be intact, deficient, or abnormally thickened. Even when the cartilage is intact, however, the cartilage may still be abnormal. These lesions are associated with abnormal fibrovascular tissue at the cartilage/bone interface which manifests as T2-bright cystic appearing lesions at MRI [65].

Normal ossification variants of the femoral condyles may mimic OCD on radiography and MRI. The confusion between the two (normal variation in ossification versus OCD) may also explain why the prognosis is better for juvenile OCD compared to adult forms. Ossification variants are also more common in patients with OCD, but they regress spontaneously and do not evolve into an OCD [66]. They are located within the posterior third of the femoral condyle, lack surrounding marrow edema, and generally have a wedge-shaped configuration [66]. These ossification variants regress spontaneously.

Knee Injuries in Older Children, Adolescents, and Adults

Ligamentous sprains, soft tissue contusions, and muscle strains far outnumber osseous lesions in the lower extremity after trauma in general [6, 67], though in pediatric patients, ligamentous injuries are less common than physeal injuries [1]. The knee is a commonly injured joint, and numerous studies have shown that MRI is the imaging modality of choice to identify *meniscal*, *ligament*, *chondral*, *and nondisplaced bone injuries* around the knee [68]. A *Segond fracture* which is seen on a radiograph is, while small, clinically relevant because of its high association with ACL tears and meniscal tears in most cases [69].

Patellar fractures may be sustained by direct trauma or an avulsion fracture at the site of tendon attachments. These fractures are caused by a rapid contraction of the quadriceps muscle. The patella has several central ossification centers, and ossification progresses peripherally during growth. The injury may not be visible on radiographs if bone is not avulsed with the cartilage, but the stripped cartilage may go on to ossify on follow-up radiographs. Patella alta may be the sole radiographic evidence of the injury. For imaging findings of *transient patellar dislocation*, MRI is more sensitive than radiographs, including injury to the medial patellofemoral ligament, bone contusions, and osteochondral injuries [1, 6, 70].

In severely injured patients in which knee dislocation, a tibial plateau fracture or another *complex knee injury* is suspected, multidetector CT may be a useful alternative to radiography and MRI because it is fast and has demonstrated satisfying diagnostic accuracy [6].

What Is the Imaging Approach to Long Bone Fractures in Adults and Children?

Summary of Evidence There are scarcely any evidence-based guidelines or algorithms for the imaging of long bone injury available. Therefore, clinicians have to rely on professional judgment when requesting imaging studies based on presenting signs and symptoms of the patient. Radiography is the only imaging tool that is necessary in most cases; however, this knowledge is based rather on a large number of clinical observations and pictorial essays than on results of diagnostic accuracy studies (moderate evidence). Magnetic resonance imaging has replaced scintigraphy and is superior to CT as confirmation test used in the evaluation of stress fractures (strong evidence).

Supporting Evidence The *femur* is the longest and strongest bone within the body and therefore requires a significant amount of force to cause a fracture. Although these injuries are often associated with additional injuries including additional fractures, dislocations, and ligamentous or meniscal injuries of the knee [71, 72], isolated femur fractures are more common in children than in adults. Femoral diaphyseal fractures are categorized based on the *Arbeitsgemeinschaft für Osteosynthesefragen* or Society for Bone Healing (AO) Foundation or Müller classification [73]. The femur is a common location for pathologic fractures, and it is important to scrutinize imaging studies of the fractured bone for signs of a focal lesion or a more diffuse, bone-weakening process. Anteroposterior and lateral radiographs are indicated in the evaluation of any potential femur fracture. Cross-table lateral radiographs of the femur can be performed without moving the femur and are often the preferred lateral view in a patient with significant pain or disability after trauma. If the patient is able to move without significant pain, and the injury is more distal in the thigh, a frog-leg lateral view may be preferred.

If a femoral stress fracture is suspected, radiography should be the initial imaging evaluation. If radiographs are negative and symptoms persist, the study should be repeated in 10–14 days [74]. For further evaluation, MRI may be considered because it is very sensitive and specific and outperforms other imaging modalities in this regard [74].

Tibia fractures are the third most common long bone fracture in children [75]. In younger children, twisting injuries and low-energy falls account for the majority of injuries, including the classic toddler's fracture. In older children, adolescents, and adults, sports-related injuries and motor vehicle accidents are the most common mechanisms of injury. In 30% of cases, there is an associated fibular fracture [76]. The internal oblique radiograph increases the conspicuity of a tibial toddler's fracture and should be obtained if the initial AP and lateral radiographs are normal, and there is high clinical concern [77]. In a young child who is non-weight-bearing, radiographs of the tibia only are as effective as total lower extremity radiographs when there are no localizing signs [78]. Radiation and cost can be spared by reserving additional imaging to the non-weight-bearing child for patients with localizing signs and/or negative tibia radiographs [78].

Magnetic resonance imaging should be considered if there is a concern for a stress fracture when no fracture line is noted on radiographs [13, 74]. They most commonly occur at the posteromedial tibial border.

Fractures of the tibial shaft vary in appearance depending on the mechanism of injury. Spiral fractures tend to be the result of a twisting injury, such as rotating the body around a fixed foot. In toddlers, the force required to cause a spiral fracture may be insubstantial [77], whereas in older children, adolescents, and adults, these injuries are often the result of high-force injuries sustained in sporting activities. Direct trauma to the lower leg results in a transverse fracture through the diaphysis. Buckle fractures (or torus fractures) may be caused by axial-loading injuries or compressive forces along the long axis of the cortex, leading to buckling of the cortex. These may occur in the proximal tibia or the distal fibula. Lastly, bowing fractures are uncommon in the lower leg and usually affect the fibula secondary to an axial-loading injury that causes cortical microfractures [78].

A fracture of the proximal *fibula* with an associated ankle joint injury is termed a Maisonneuve fracture after the French surgeon who first described it in 1840 [79]. This type of fracture is seen in 7% of ankle injuries [80]. This is a rare but important fracture because it may be missed in the setting of ankle injury if the pattern of injury is not well understood. The presence of a Maisonneuve fracture indicates underlying ligamentous ankle injury such as deltoid ligament tear, tibiofibular ligament tear, or interosseous membrane rupture/avulsion. Static images of the ankle may appear normal, while stress images reveal widening of the tibiofibular syndesmosis and lateral talar shift, which is an unstable injury that may require operative fixation [81]. When these findings are noted, dedicated imaging of the proximal fibula is useful for detecting Maisonneuve fracture [81].

What Is the Imaging Approach to Ankle and Foot Injuries?

Summary of Evidence Based on strong evidence, clinical decision rules such as the Ottawa ankle rules (OAR) and the low-risk ankle rule (LRAR) are highly sensitive for predicting which patients have sustained a significant foot or ankle fracture that requires treatment. These rules may miss a small number of insignificant fractures in very young children who are either non-ambulatory or nonverbal and unable to localize symptoms, and therefore some variation in practice exists among pediatric clinicians in deciding how and when to image these youngest patients. For patients, both adults and children of >5 years, meeting the criteria of those rules, radiography is the primary imaging modality and in many instances, the only one required (strong evidence). Cross-sectional imaging has a limited role in ankle and foot injuries and may be considered on a case-by-case basis when radiographs are normal or in specific injuries, e.g., in talus fracture or osteochondral injury (moderate evidence).

Supporting Evidence The Ottawa ankle rules (OAR) are guidelines meant to help physicians determine the need for imaging after ankle and foot injury [82] (Table 31.2). These rules have been validated as an effective screening tool in adults [5, 83–85] and state that tenderness over the lateral malleolus, inability to bear weight, and tenderness over the posterior tibia and fibula are all indications for radiographs. Ottawa ankle rules apply to patients who are ambulating and who can verbalize pain symptoms [86, 87]. Application of clinical decision rules does have the ability to decrease radiographs by up to 62% [88–90]. Studies have shown that the OAR can be applied also to children with excellent validity. Sensitivity for detecting fracture in children using OAR is 95–100% [86, 90–93] with an estimate for overall reduction in radiograph by ~24% [92, 93]. These results are similar to those achieved for the evaluation of the OARs in adult patients, shown, e.g., by a systematic review of 32 studies [94]. The low-risk ankle rule (LRAR) is another clinical decision-based rule indicating that radiographs are necessary in any child with tenderness and/or swelling isolated to the distal fibula and/or the adjacent lateral ligaments distal to the tibial anterior joint line. The LRAR has been shown to detect 100% of high-risk fractures in children and reduce radiographs in 62.8% of children with low-risk examinations [89]. The LRAR is not widely known or applied by emergency physicians in the USA [88].

Physeal Fractures in Pediatric Patients

Radiographs are the mainstay of imaging ankle and foot injuries in the pediatric population [9]. The *distal tibia* is one of the most common locations for an *epiphyseal injury* in a child, second only to the distal radius [95] and finger. As is true of all physeal injuries, it may be difficult to distinguish a subtle physeal fracture from the normal irregularity and undulation of the physis. There is a normal undulation within the medial aspect of the distal tibial physis where physeal fusion begins, which is termed “Kump’s bump” [96]. Physeal closure of the distal tibia takes approximately 18 months to complete once it has begun and follows a typical pattern of closure. The distal fibula usually fuses 1–2 years after the distal tibial physis. There are various accessory ossification centers of the distal fibula and tibia that contribute to growth and may be mistaken for fractures. The os subfibulare is present in 2.1% of the population [97]. These accessory ossification centers may be mistaken for fractures after an ankle injury, but the round shape and well-corticated margins, as well as the location, usually point toward the correct diagnosis. In some cases, the clinical history may be confounding, as patients may sustain stress injuries at the accessory ossicles related to motion at insertion sites of the talofibular ligaments directly onto the ossicle [98]. A standard Salter 2 fracture of the distal tibia is the most common ankle fracture with premature physeal fusion occurring in 25% [99].

The *triplane fracture* is a distinct type of fracture that occurs in the distal tibia of skeletally immature patients near the end of growth. Aptly named, the triplane fracture consists of three distinct components: a vertical epiphyseal fracture, a horizontal physeal fracture, and an oblique metaphyseal fracture. Minimally displaced, extra-articular triplane fractures may be treated conservatively, while surgery may be indicated for fractures with >2 mm articular surface step-off. While radiographs are usually diagnostic of the fracture, computed tomography may be helpful in making this determination if there is concern for displacement of fragments. Computed tomography of complex tibial fractures does not improve fracture classification or treatment decision, though it has been reported to help surgeons plan surgery [100].

The *juvenile Tillaux fracture* is a Salter 3 fracture with a vertical component through the epiphysis and a horizontal fracture through the physis. The insertion of the anterior inferior tibiofibular ligament on the lateral aspect of the distal tibial epiphysis results in various degrees of avulsion and displacement of the lateral epiphyseal fracture fragment when such an injury is sustained. The pattern of these fractures, particularly the propagation of the fracture plane through the lateral aspect of the physis, is very much related to the ossification pattern of the distal tibia, given that physeal fusion begins anteromedially and progresses posteriorly and laterally, such that the lateral portion of the physis may be the only portion that remains unfused at the time of injury [101].

Radiographs remain the mainstay for diagnosis and characterization of distal tibia and fibular fractures. Findings to note on radiographs include the degree of epiphyseal displacement, widening of the physis, and alignment of articular surfaces [95]. Computed tomography is reserved for further evaluation of injuries when surgery is being considered [100]. Computed tomography or MRI may be used to characterize and quantify the amount of growth arrest and physeal bar formation after fracture healing.

Although the fibula is not the primary weight-bearing bone in the ankle, *distal fibular fractures* also occur though with less frequency than fractures of the tibia. The physis of the fibula fuses after the distal tibial physis [101], and therefore it should not be concerning to see an open fibular physis even if the tibial physis is fused. Salter fractures of the fibula may be detected on radiographs with soft tissue swelling centered at the physis and widening or asymmetry of the physis as clues to the presence of an underlying fracture. About 7% of children with lateral malleolar tenderness after ankle sprain and normal radiographs will have an occult distal fibular fracture, as evidenced by healing on follow-up radiographs [102]. Radiographs often "overcall" the presence of a Salter I fracture of the distal fibula when compared to MRI [103]. Despite this, there is no convincing evidence the support the routine use of MRI for evaluation of distal fibular fractures after ankle sprain [102, 103].

Sever's lesion, otherwise known as calcaneal apophysitis, is the most common overuse injury seen in school-age children [67]. It is also the most common cause of heel pain in skeletally immature athletes. It is considered a self-limiting condition characterized by heel pain with running or jumping activities. The diagnosis is most often made clinically by eliciting pain during medial and lateral compression of the heel at the attachment site of the calcaneal apophysis. While radiographs are often requested to evaluate for Sever's disease, there are no radiographic imaging signs that are considered to be sensitive for the diagnosis. When radiographs are performed, the goal is to evaluate for other pathology that could explain the pain (such as calcaneal fracture) rather than to confirm a diagnosis of Sever's [102].

The open epiphyseal plate is a potential site of weakness in the developing pediatric skeleton. Salter 1 *fractures of the phalanges* of the toes may be subtle on AP radiographs of the foot, particularly when nondisplaced. These injuries best detected on oblique radiographs manifested as widening and irregularity of the physes [26].

Intra-articular fractures of the great toe are a unique fracture in the pediatric population. These fractures often involve the proximal phalanx of the great toe and are the result of hyperflexion from a direct impact. The physis of the proximal phalanx is located at the base of the phalanx and is highly susceptible to injury. These fractures are most common in children who are near skeletal maturity. Radiographs are usually all that is required for diagnosis and management planning for these patients. In general, unless there is >2 mm of displacement of the fracture fragment, they are usually managed conservatively and nonoperatively [103].

Specific Ankle and Foot Injuries in Children, Adolescents, and Adults

Ankle sprains are common injuries in both children and adults. Ligament injuries in the ankle are the most frequent sports injury [104]. Most of these injuries are inversion injuries with damage to the lateral ligamentous structures in the ankle, though uncommonly an eversion-type injury may occur. The lateral collateral ligament complex is the most commonly injured and consists of the anterior talofibular (ATFL), calcaneofibular (CFL), and posterior talofibular ligaments (PTFL). Of these, the ATFL is the most commonly injured, followed by CFL and then PTFL [104, 105]. “High” ankle sprains refer to an injury of the syndesmotic ligaments. On radiographs, the presence of abnormal widening of the joint space may point toward an underlying ligamentous rupture. While MRI is more sensitive for detection of ligamentous injuries in the ankle of patients after a sprain injury, MRI findings sometimes do not correlate with clinical findings and do not bring additional therapeutic value to the work-up of the patient in the acute setting [14, 106]. Therefore, although MRI may detect ligamentous injury, there is little evidence to support routine use of MRI in the evaluation of ankle sprains.

Osteochondral lesions in the ankle are injuries to the talus that involve both the bone and the overlying cartilage. They can occur after a single traumatic injury or as a result of repeated trauma. Radiography cannot demonstrate cartilage or bone contusions related to those lesions. Therefore, MRI is the diagnostic modality of choice to evaluate for these injuries [5].

A significant minority of patients with ankle trauma are diagnosed with *syndesmotic injury*. Due to limitations of the physical examination and radiography in establishing the diagnosis, MRI should be performed in cases which need further evaluation and/or to avoid misdiagnosis [5].

Talar fractures are relatively uncommon and usually sustained after high-impact trauma. There are multiple varieties of talar fractures, defined by the anatomic areas involved with the fracture (talar head, neck, body, etc.) [107]. The lateral process talar fracture has an unusually high prevalence in snowboarders, victims of motor vehicle collisions, and falls secondary to an external rotation force placed on a dorsiflexed foot during axial loading [107]. These fractures are frequently missed on radiographs [5, 108], and CT imaging may be considered in patients with negative ankle radiographs but a high suspicion of injury. There are no strict imaging recommendations in this regard.

Fractures of the foot are common in both adults and children, and the *metatarsals* are among the bones most commonly *fractured*. Acute foot fractures of normal bones are usually caused by the dropping of heavy objects on the foot or by stress associated with abnormal repetitive trauma. In deficient bones, insufficiency fractures may result from normal stress. The mechanism for metatarsal fractures differs between older and younger patients. Patients greater than age 5 years are more likely to fracture a metatarsal while falling on a level surface or twisting their foot, while younger patients under the age of 5 years are more likely to fracture a metatarsal after falling from a height.

Patients with concern for midfoot injury and possible *Lisfranc joint disruption* should undergo three-view radiographic evaluation of the foot, with weight-bearing on at least the AP view [4].

If radiographs are normal, MRI may then be considered on a case-by-case basis [4].

In suspected *acute tendinous rupture or dislocation in the foot*, radiography may be indicated, but findings often are negative. As second-line imaging studies and if the patient's condition fails to improve, MRI or US has been suggested, and both show similar sensitivities for tendon injuries about the foot and ankle, specifically the tibialis posterior tendon [5].

Take-Home Tables

See Tables 31.1 [109] and 31.2; highlight and summarize suggested radiographic views for lower extremity trauma and clinical decision rules for radiography of acute knee, ankle, or foot injury, respectively.

Take-Home Points

The Ottawa Knee Rule

The Ottawa knee rule was derived to aid in the efficient use of radiography in acute knee injuries:

- The rule has been prospectively validated on multiple occasions in different populations and in both children and adults.
- Numerous studies found sensitivities for the Ottawa knee rules of 98–100% for clinically significant knee fractures. One study did find a sensitivity of just 86%.
- Specificities for the Ottawa knee rules typically range from 19% to 50%, though the rule is not designed/intended for specific diagnosis.
- When used appropriately, the amount of knee X-rays obtained can be reduced by around 20–30%.
- The Ottawa knee rules are useful in ruling out fracture (high sensitivity) when negative, but poor for ruling in fractures (many false positives).

Tips for Use of the Ottawa Knee Rule

- Tenderness of patella is significant only in an isolated finding.
- Use only for injuries <7 days.
- "Bearing weight" counts even if the patient limps.

Precautions for Use of the Ottawa Knee Rule

- Clinical judgment should prevail if examination is unreliable:
  - Intoxication
  - Uncooperative patient
  - Distracting painful injuries
  - Diminished sensation in legs
- Always provide written instructions.
- Encourage follow-up in 5–7 days if pain and ability to walk is not better.
- The Ottawa knee rules should be applied to all patients aged 2 and older with knee pain/tenderness in the setting of trauma.
- Patients without criteria for imaging by the Ottawa knee rules are highly unlikely to have a clinically significant fracture and do not need plain radiographs.
- Application of the Ottawa knee rules can cut down on the number of unnecessary radiographs by 20–30%, which has proven to be cost effective for patients without reducing quality of care.

The Ottawa Ankle Rule

The Ottawa ankle rule was derived to aid in the efficient use of radiography in acute ankle and midfoot injuries:

- The rule has been prospectively validated on multiple occasions in different populations and in both children and adults.
- Sensitivities for the Ottawa ankle rule range from the high 90% to 100% range for "clini-

cally significant" ankle and midfoot fractures. This is defined as a fracture or an avulsion greater than 3 mm.
- Specificities for the Ottawa ankle rule are approximately 41% for the ankle and 79% for the foot, though the rule is not designed/intended for specific diagnosis.
- The Ottawa ankle rule is useful in ruling out fracture (high sensitivity), but poor for ruling in fractures (many false positives).

Tips for Use of the Ottawa Ankle Rule

- Palpate the entire distal 6 cm of the fibula and tibia.
- Do not neglect the importance of medial malleolar tenderness.
- "Bearing weight" counts even if the patient limps.
- Be caution in patients under age 18.

Precautions for Use of the Ottawa Ankle Rule

- Clinical judgment should prevail if examination is unreliable:
  - Intoxication
  - Uncooperative patient
  - Distracting painful injuries
  - Diminished sensation in legs
  - Gross swelling which prevents palpation of malleolar tenderness
- Always provide written instructions.
- Encourage follow-up in 5–7 days if pain and ability to walk is not better.
- The Ottawa ankle rule should be applied to all patients aged 2 and older with ankle or midfoot pain/tenderness in the setting of trauma.
- Patients without criteria for imaging by the Ottawa ankle rule are highly unlikely to have a clinically significant fracture and do not need plain radiographs.
- Application of the Ottawa ankle rules can reduce the number of unnecessary radiographs by as much as 25–30%, improving patient flow in the ED.

Imaging Case Studies

Case 1

Figure 31.1a, b presents a 75-year-old woman who has fallen and has left buttock pain.

Case 2

In Fig. 31.2a, b, a 46-year-old man presents with a sports injury.

Case 3

In Fig. 31.3a, b, a 36-year-old man presents with a sports-related injury.

Case 4

Figure 31.4a, b shows a 14-year-old male with right AIIS (anterior inferior iliac spine) avulsion.

Case 5

A Salter 1 fracture of the distal femur in a 13-year-old female is presented in Fig. 31.5a, b.

Case 6

Figure 31.6a, b presents a triplane fracture of the tibia in a 12-year-old female.

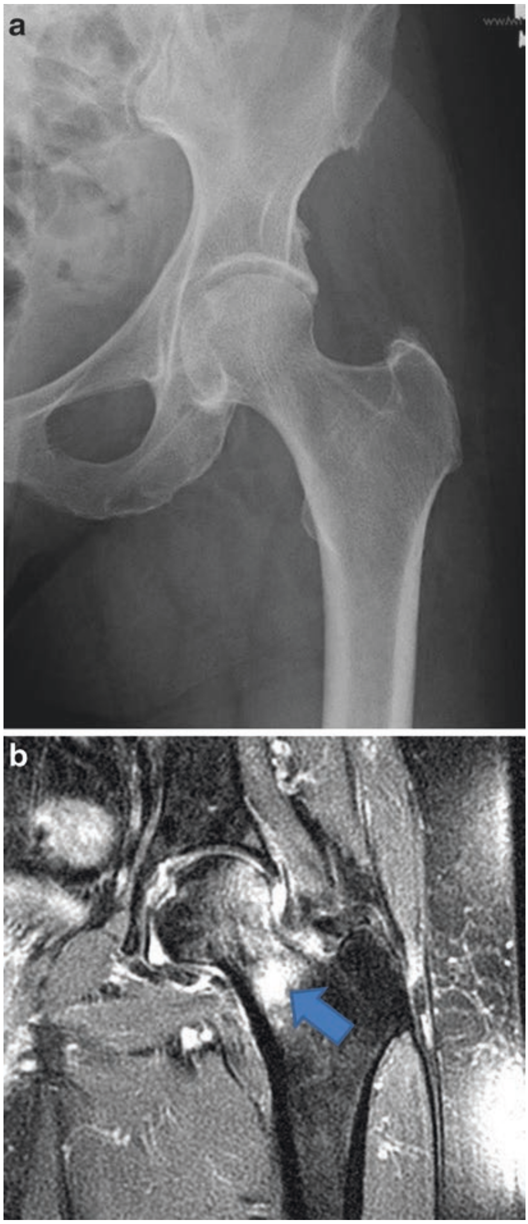

Fig. 31.1 **A** 75-year-old woman with fall and left buttock pain. (**a**) Frontal radiograph of the left hip does not reveal a fracture. (**b**) Coronal proton density fat-suppressed (PDFS) MR image shows a band of high signal (*blue arrow*) through the femoral neck, which had corresponding linear low signal on T1-weighted images, consistent with a radiographically occult, nondisplaced fracture (Images kindly provided by Dr. Kara Gaetke-Udager, University of Michigan Health System, Ann Arbor, MI, USA)

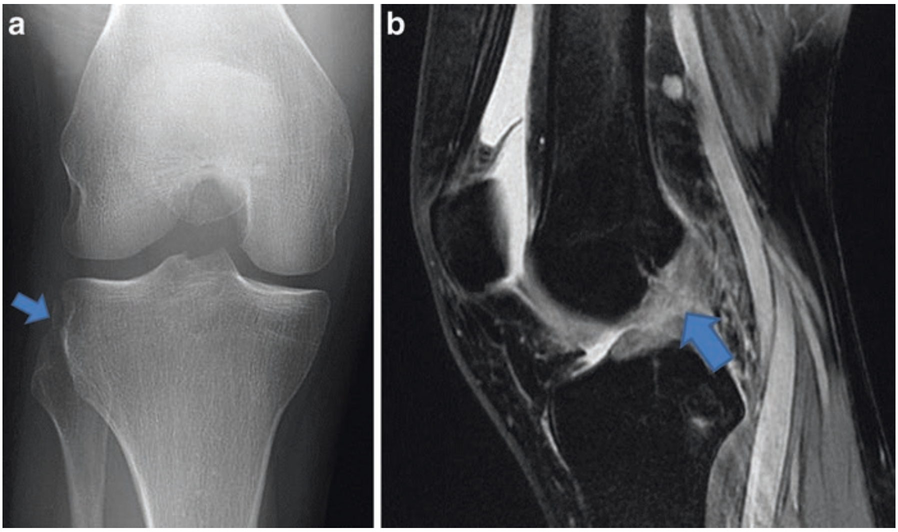

Fig. 31.2 A 46-year-old man with a sports injury. (**a**) Frontal radiograph of the knee shows that there is a mildly displaced, small fracture fragment seen along the lateral tibial plateau, consistent with a Segond fracture (*blue arrow*). (**b**) Sagittal PDFS MR image shows a complete tear of the anterior cruciate ligament (ACL) (*block blue arrow*), which is associated with Segond fractures (Images kindly provided by Dr. Kara Gaetke-Udager, University of Michigan Health System, Ann Arbor, MI, USA)

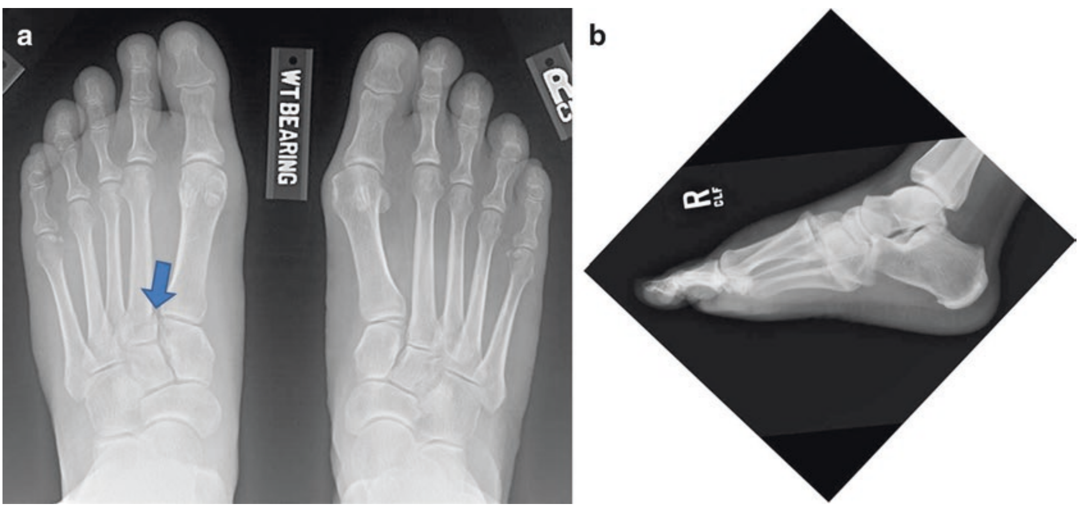

Fig. 31.3 A 36-year-old man with a sports-related injury. (**a**) Bilateral standing AP radiograph of the feet shows asymmetric widening of the left Lisfranc joint with a minimally displaced fracture of the base of the second metatarsal (*blue arrow*), consistent with a Lisfranc fracture/dislocation. (**b**) Lateral radiograph of the left foot shows dislocation of the first tarsometatarsal (TMT) joint with the base of the first metatarsal mal-aligned with the cuneiform (Images kindly provided by Dr. Kara Gaetke-Udager, University of Michigan Health System, Ann Arbor, MI, USA)

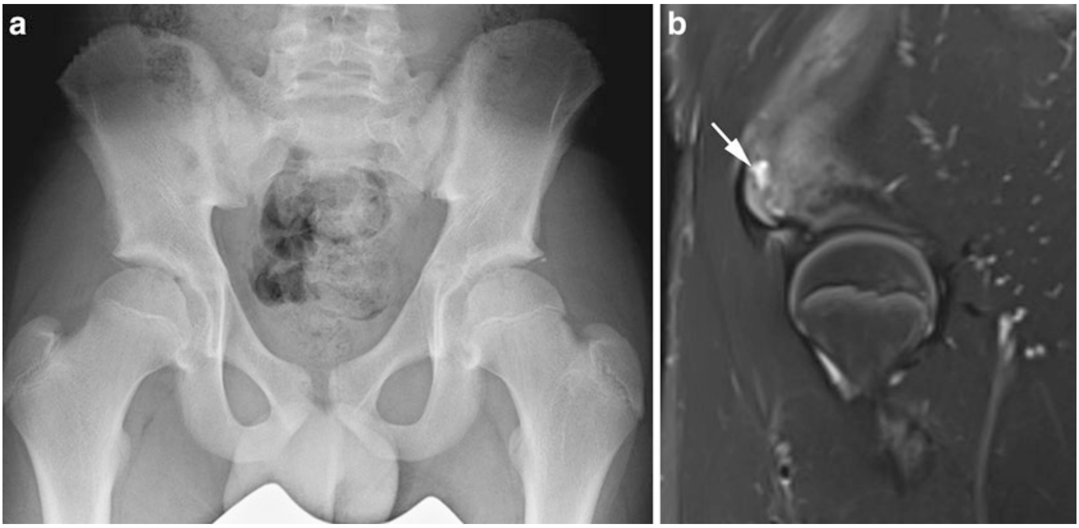

Fig. 31.4 A 14-year-old male with right AIIS (anterior inferior iliac spine) avulsion. (**a**) Radiograph of the pelvis is normal. (**b**) Sagittal FSEIR images from an MRI of the pelvis demonstrates abnormal marrow signal within the right AIIS and the surrounding iliac bone with fluid separating the apophysis from the bone (*arrow*)

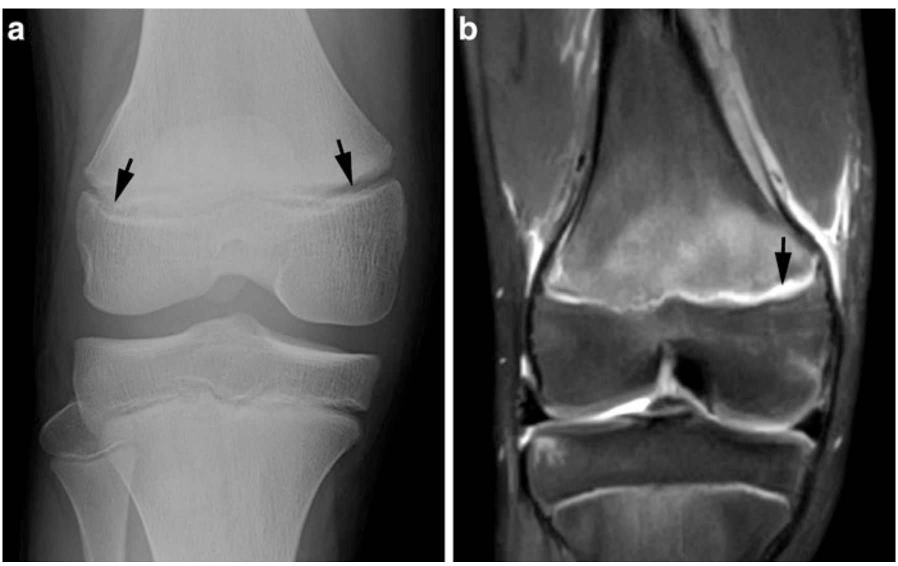

Fig. 31.5 Salter 1 fracture of the distal femur in a 13-year-old female. (**a**) The AP radiograph of the knee demonstrates abnormal widening of the distal femoral physis (*black arrows*). (**b**) Coronal proton density-weighted magnetic resonance image with fat suppression of the knee demonstrates abnormal fluid signal within the physis (*black arrow*) and abnormal marrow edema within the metaphysis

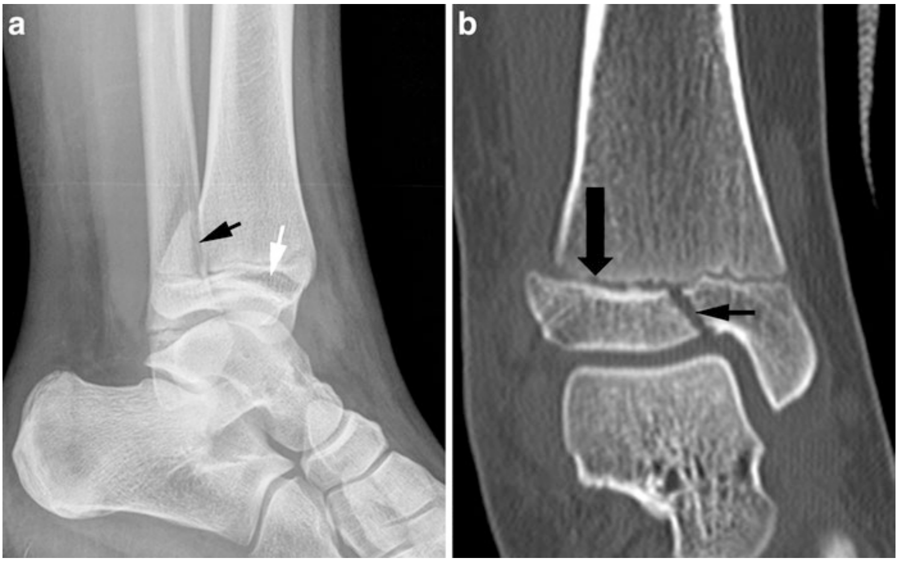

Fig. 31.6 Triplane fracture of the tibia in a 12-year-old female. (**a**) Lateral radiograph of the ankle demonstrates widening of the distal tibial physis (*white arrow*) and fracture line within the tibial metaphysis (*black arrow*). (**b**) Coronal reformatted image from a CT study demonstrates the vertical fracture line extending into the epiphysis (*small black arrow*). There is widening of the lateral aspect of the physis (*large black arrow*). The involvement of both the metaphysis and epiphysis makes this fracture a Salter-Harris type IV fracture

Future Research

- Recommendation for specific radiographic views in the setting of pediatric hip injury: algorithms for the specific views that are most indicated in different clinical settings
- Indications for MRI in the acutely injured child
- Indications for CT in the setting of lower extremity injury in both children and adults

References

1. Gill KG, Nemeth BA, Davis KW. Magn Reson Imaging Clin N Am. 2014;22:743–63.
2. Lambers K, Ootes D, Ring D. Clin Orthop Relat Res. 2012;470:284–90.
3. Polinder S, Meerding WJ, van Baar ME, et al. J Trauma. 2005;59:1283–91.
4. Bancroft LW, Kransdorf MJ, Adler R, et al. J Am Coll Radiol. 2015;12(6):575–81.
5. Mosher TJ, Kransdorf MJ, Adler R, et al. J Am Coll Radiol. 2015;12:221–7.
6. Tuite MJ, Kransdorf MJ, Beaman FD, et al. J Am Coll Radiol. 2015;12:1164–72.
7. Ward RJ, Weissman BN, Kransdorf MJ, et al. J Am Coll Radiol. 2014;11:114–20.
8. McCauley RG, Schwartz AM, Leonidas JC, et al. Radiology. 1979;131:95–7.
9. Vanhoenacker FM, Bernaerts A, Gielen J, et al. JBR-BRT. 2002;85:212–8.
10. Pandya NK, Edmonds DW, Roocroft JH, Mubarak SJ. J Pediatr Orthop. 2012;32:749–59.
11. Crawford AH. J Pediatric Orthop. 2012;32:S69–73.
12. Rosenbaum AJ, DiPreta JA, Uhl RL. Orthopedics. 2012;35:1046–9.
13. Naranja RJ Jr, Gregg JR, Dormans JP, et al. Clin Orthop Relat Res. 1997;342:141–6.
14. Endele D, Jung C, Bauer G, Mauch F. Foot Ankle Int. 2012;33:1063–8.
15. Cho KH, Lee SM, Lee YH. Suh KJ. Korean J Radiol. 2010;11:84–94.
16. Barata I, Spencer R, Suppiah A, et al. Pediatr Emerg Care. 2012;28:1154–7.
17. Rosenborg M, Mortensson W. Acta Radiol Diagn. 1986;27:85–9.
18. Sciarretta JD, Macedo FI, Chung EL, et al. J Trauma Acute Care Surg. 2014;76:1386–9.
19. Wojtowycz M, Starshak RJ, Sty JR. Radiology. 1980;136:647–8.
20. Jarrett DY, Kramer DE, Callahan MJ, Kleinman PK. Pediatr Radiol. 2013;43:S2–7.
21. Hayashi D, Hamilton B, Guermazi A, et al. Insights Imaging. 2012;3:591–601.
22. Grant TH, Kelikian AS, Jereb SE, McCarthy RJ. J Bone Joint Surg Am. 2005;87:1788–94.

23. Khoury V, Guillin R, Dhanju J, Cardinal E. Sem Musculoskel Radiol. 2007;11:149–61.
24. Stevens MA, El-Khoury GY, Kathol MH, et al. RadioGraphics. 1999;19:655–72.
25. Sundar M, Carty H. Skeletal Radiol. 1994;23:85–90.
26. Swischuk LE. Emerg Radiol. 2015;20:543–4.
27. Rossi F, Dragoni S. Skeletal Radiol. 2001;30:127–31.
28. De Paulis F, Cacchio A, Michelini O, et al. Eur J Radiol. 1998;27:S49–59.
29. Wootton JR, Cross MJ, Holt KWG. J Bone Joint Surg Br. 1990;72:625–7.
30. Davis K. Radiol Clin N Am. 2010;48:1213–35.
31. Gholve PA, Cameron DB, Millis MB. Curr Opin Pediatr. 2009;21:39–45.
32. Peck D. Am Fam Physician. 2010;82:258–62.
33. Aronsson DD, Loder RT, Breuer GJ, Weinstein SL. J Am Acad Orthop Surg. 2006;14:666–79.
34. Causey AL, Smith ER, Donaldson JJ, et al. J Emerg Med. 1995;13:175–89.
35. Pinkowsky GJ, Hennrikus WL. J Pediatr. 2013;162:804–7.
36. Jarrett DY, Matheney T, Kleinman PK. Pediatr Radiol. 2013;43:S71–82.
37. Dwek JR. Magn Reson Imaging Clin N Am. 2009;17:509–20.
38. Blanchard C, Kushare I, Boyles A, et al.; J Pediatr Orthop 2015.; Epub ahead of print.
39. Hearty T, Swaroop VT, Gourineni P, Robinson L. J Orthop Trauma. 2011;25:e68–73.
40. Mayer S, Stewart JR, Fadell MF, et al. Pediatr Radiol. 2015;45:1355–62.
41. Laorr A, Greenspan A, Anderson MW, et al. Skeletal Radiol. 1995;24:239–45.
42. Novais EN, Hear TC, Hill MK, Mayer SW. J Pediatr Orthop. 2015. Epub ahead of print.
43. Boardman MJ, Herman MJ, Buck B, Pizzutillo PD. J Am Acad Orthop Surg. 2009;17:162–73.
44. Spence D, DiMauro JP, Miller PE, et al. J Pediatr Orthop. 2015. Epub ahead of print.
45. Shin AY, Morin WD, Gorman JD, et al. Am J Sports Med. 1996;24:168–76.
46. Feldman F, Staron RB. AJR. 2004;183:323–9.
47. Schultz E, Miller TT, Boruchov SD, et al. Radiology. 1999;211:237–40.
48. Alam A, Willett K, Ostlere S. J Bone Joint Surg Br. 2005;87:1253–5.
49. Galloway HR, Meikle GR, Despois M. Australas Radiol. 2004;48:21–4.
50. Bogost GA, Lizerbram EK, Crues JV III. Radiology. 1995;197:263–7.
51. Lee YP, Griffith JF, Antonio GE, et al. Hong Kong Med J. 2004;10:271–5.
52. Khan SK, Kalra S, Khanna A, et al. Injury. 2009;40:692–7.
53. Stiell IG, Wells GA, Hoag RH, et al. JAMA. 1997;278:2075–9.
54. Stiell IG, Greenberg GH, Wells GA, et al. Ann Emerg Med. 1995;26:405–12.
55. Vijayasankar D, Boyle AA, Atkinson P. Emerg Med J. 2009;26:250–3.
56. Bulloch B, Neto G, Plint A, et al. Ann Emerg Med. 2003;42:48–55.
57. Moore BR, Hampers LC, Clark RD. J Emerg Med. 2005;28:257–61.
58. Smith NC, Parker D, McNicol D. J Pediatr Orthop. 2001;21:600–3.
59. Butcher CC, Hoffman EB. J Pediatr Orthop. 2005;25:145–8.
60. Carey J, Spence L, Blickman H, Eustace S. Skeletal Radiol. 1998;27:250–5.
61. Close BJ, Strouse PJ. Pediatr Radiol. 2000;30:756–62.
62. Lafrance R, Giordano B, Goldblatt J, et al. J Am Acad Orthop Surg. 2010;18:395–405.
63. Kijowski R, Blankenbaker DG, Shinki K, et al. Radiology. 2008;248:571–8.
64. Kessler JI, Weiss JM, Nikizad H, et al. Am J Sports Med. 2014;42:2165–71.
65. Merrow AC, Reiter MP, Zbojniewicz AM, Laor T. Pediatr Radiol. 2014;44:1436–45.
66. Jans L, Jaremko J, Ditchfield M, et al. Eur J Rad. 2012;81:3384–9.
67. Jespersen E, Rexen CT, Franz C, et al. Scand J Med Sci Sports. 2015;25:251–8.
68. Puig S, Kuruvilla JC, Ebner L, Endel G. Skeletal Radiol. 2015;44:1427–34.
69. Goldman AB, Pavlov H, Rubenstein D. AJR. 1988;151:1163–7.
70. Earhart C, Patel DB, White EA, et al. Emerg Radiol. 2013;20:11–23.
71. Cannon SR, Pool CJ. Injury. 1983;15:156–8.
72. Bennett FS, Zinar DM, Kilgus DJ. Clin Orthop Relat Res. 1993;296:168–77.
73. Müller ME. Unfallheilkunde. 1980;83:251–9.
74. Daffner RH, Weissman BN, Appel M, et al. ACR Appropriateness Criteria®. Stress (fatigue/insufficiency) fracture. http://www.acr.org.
75. Palmu SA, Auro S, Lohman M, et al. Acta Orthop. 2014;85:513–7.
76. Mashru RP, Herman MJ, Pizzutillo PD. J Am Acad Orthop Surg. 2005;13:345–52.
77. Tenenbein M, Reed MH, Black GB. Am J Emerg Med. 1990;8:208–11.
78. John SD, Moorthy CS, Swischuk LE. RadioGraphics. 1997;17:367–76.
79. Hunter TB, Peltier LF, Lund PJ. RadioGraphics. 2000;20:819–36.
80. Hinds RM, Tran WH, Lorich DG. Orthopedics. 2014;37:e1040–4.
81. Hanson JA, Fotoohi M, Wilson AJ. AJR. 1999;173:702.
82. Stiell IG, Greenberg GH, McKnight RD, et al. JAMA. 1993;269:1127–32.
83. Bachman LM, Kolb E, Koller MT, et al. BMJ. 2003;326:417.
84. Stiell I, Wells G, Laupacis A, et al. BMJ. 1995;311:594–7.

85. Leddy JJ, Kesari A, Smolinski RJ. Med Sci Sports Exerc. 2002;34:57–62.
86. Myers A, Canty K, Nelson T. Arch Dis Child. 2005;90:1309–11.
87. Dowling SK, Wishart I. CJEM. 2011;13:333–8.
88. Boutis K, Constantine E, Schuh S, et al. Acad Emerg Med. 2010;17:709–17.
89. Boutis K, Komar L, Jaramillo D, et al. Lancet. 2001;358:2119–21.
90. Plint AC, Bulloch B, Osmond MH, et al. Acad Emerg Med. 1999;6:1005–9.
91. Clark KD, Tanner S. Pediatr Emerg Care. 2003;19:73–8.
92. Dowling S, Spooner CH, Liang Y, et al. Acad Emerg Med. 2009;16:277–87.
93. Al Omar MZ, Baldwin GA. Emerg Radiol. 2002;9:88–92.
94. Bachmann LM, Kolb E, Koller MT. BMJ. 2003;326:417.
95. Rogers LF, Poznanski AK. Radiology. 1994;191:297–308.
96. Kump WL. Radiology. 1966;97:676–81.
97. Blackburn EW, Aronsson DD, Rubright JH, Lisle JW. J Bone Joint Surg Am. 2012;94:1234–44.
98. Pill SG, Hatch M, Linton JM, Davidson RS. J Bone Joint Surg Am. 2013;95(e115):1–6.
99. Leary JT, Handling M, Talerico M, et al. J Pediatr Orthop. 2009;29(4):356–61.
100. Thawrani D, Kuester V, Gabos PG, et al. J Pediatr Orthop. 2011;31:745–50.
101. Chung T, Jaramillo D. Radiology. 1995;194:227–32.
102. Rachel JN, Williams JB, Sawyer JR, et al. J Pediatr Orthop. 2011;31:548–50.
103. Kramer DE, Mahan ST, Hresko MT. J Pediatr Orthop. 2014;34:144–9.
104. Park HJ, Cha SD, Kim SS, et al. Clin Radiol. 2012;67:313–8.
105. Perrich KD, Goodwin DW, Hecht PJ, Cheung Y. AJR. 2009;193:687–95.
106. Nikken JJ, Oei EH, Ginai AZ, et al. Radiology. 2005;234:134–42.
107. Melenevsky Y, Mackey RA, Abrahams RB, Thomson NB III. RadioGraphics. 2015;35:765–79.
108. Wu Y, Jiang H, Wang B, Miao W. J Pediatr Orthop. 2015. Epub ahead of print.
109. Ha AS, Porrino JA, Chew FS. AJR. 2014;203:492–500.