



# Imaging of sports injuries in adolescents

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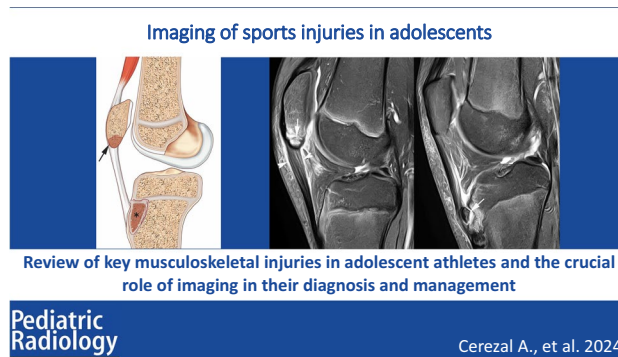
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## Abstract

Musculoskeletal injuries in adolescents tend to occur in particular locations and have distinct characteristics, as they affect an immature skeleton. Increased engagement in sports, extended training and competition periods, and early specialization in specific sports, among other factors, have contributed significantly to the rise in musculoskeletal sports injuries in adolescents. Furthermore, females show a particularly pronounced increase in sports participation, where anatomical and hormonal factors play crucial roles in the development and increased frequency of sports-related injuries. Consequently, there is a growing demand for diagnostic imaging techniques. Musculoskeletal and pediatric radiologists require a comprehensive understanding of intrinsic and extrinsic risk factors and the successive stages of skeletal development that can influence the specific characteristics of sports injuries in adolescents. These aspects are crucial for the diagnostic, prognostic, and therapeutic management of these injuries and for mitigating chronic conditions that could compromise future sports participation. This review analyzes the primary musculoskeletal injuries in adolescent athletes and highlights the pivotal role of different imaging methods in their diagnosis and management.

## Graphical abstract



**Keywords** Adolescent · Athletic injuries · Diagnostic imaging · Growth plate injuries · Magnetic resonance imaging · Ultrasonography

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## Introduction

The increasing awareness of physical fitness, along with the growing enrollment of children in sports from an early age, with aspirations of becoming professional athletes, has had a great impact on the rising participation of adolescents in sports [1–3]. Musculoskeletal injuries in adolescents tend to occur in particular locations and have distinct characteristics, as they affect a maturing skeleton [4–8]. The lack of adaptation in most sports to the motor skills of specific age groups, early sports specialization, and higher training and competition hours have led to a growing incidence of musculoskeletal injuries [9]. Moreover, the increase in

participation in sports such as soccer is even more significant among females. In this group, anatomical and hormonal factors contribute to sports-related injuries [10, 11].

Musculoskeletal and pediatric radiologists must understand the underlying risk factors associated with skeletal development in each age group, as these factors can influence injury patterns [1–3]. This understanding is crucial for accurate diagnosis and effective management to reduce the risk of chronic injuries that could jeopardize future athletic performance.

This article provides an overview of the main musculoskeletal injuries in adolescent athletes and the role of different imaging methods in their diagnosis and management.

## Epidemiology of and risk factors for sports injuries in adolescents

The progressive increase in sports participation among adolescents is directly related to an increased incidence of injuries [1–3]. Risk factors for adolescent sports injuries are classified as intrinsic or extrinsic [1–3]. Intrinsic factors include age, sex, and skeletal maturation level. Extrinsic factors include early sports specialization, high levels of training from an early age, and social pressure for early professionalization in sports [1–3]. Adjusting the intensity of training to skeletal maturity and muscle–tendon flexibility is the primary modifiable factor for reducing injuries [2].

The specific biomechanics of each sport significantly influence the location and type of injury [1–3]. In the United States of America, the popularity of throwing sports such as baseball or contact sports such as American football is associated with a high incidence of injuries such as throwing elbow, shoulder dislocations, or fractures [1, 12]. In contrast, in Europe, the sports with the highest incidence of injuries include soccer, basketball, and tennis, each with specific injuries [2, 3].

Adolescent sports injuries can be divided into two main etiological groups: traumatic and overuse injuries. Overuse injuries are a growing problem related to repetitive micro-trauma at specific anatomical locations [4, 5].

Musculoskeletal injuries more frequently occur during training [1–3]. They primarily affect the lower limbs (53.8%), followed by the upper limbs (29%) and torso/spine (11.5%) [3]. In early adolescence, fractures are the most common injuries, while after a growth spurt, ligament injuries in the lower extremities, primarily the knees and ankles, predominate [2].

Fractures occur more frequently in males and predominantly affect the upper extremities (metacarpals, phalanges, radius, and distal ulna) [2, 13].

An essential aspect of sports injuries is that the presence of previous injuries can lead to proprioceptive or biomechanical changes or scarring, favoring the occurrence of new or recurrent injuries (25%) [1].

## Bone growth in adolescents

The growth of long bones occurs through endochondral ossification. Primary growth plates at the ends of long bones are responsible for longitudinal growth [14, 15]. Secondary growth plates facilitate the growth of the secondary ossification centers in the epiphyses and apophyses and are the only growth centers in smaller bones, such as those of the carpus, tarsus, and sesamoids [16].

The growth plate, or physis, consists of orderly arranged multilayered chondrocytes [16]. Chondrocytes mature as they move from the epiphyseal side to the metaphysis, and the balance between their proliferation and endochondral ossification determines the thickness of the physal cartilage. The interface between the physal cartilage and the newly formed bone of the primary spongiosa is called the zone of provisional calcification [17].

The growth plate is surrounded by the perichondrium, which provides mechanical support and is responsible for the width growth of the plate [17]. The integrity of the epiphyseal and metaphyseal vessels is essential for ensuring endochondral ossification [14, 18].

The primary growth plate is a critical component of the immature skeleton and is particularly vulnerable to chronic overload injuries caused by impaction or distraction [14, 18].

The growth of long bones occurs more rapidly than muscle development. This asynchronous development leads to muscle stiffness, significantly affecting muscle stability and dynamics, with potential implications for injuries [7].

## Sports injuries in adolescents

### Fractures

Fractures in adolescent athletes most commonly occur in early adolescence, with a peak incidence between the ages of 13 years and 15 years [13]. Several factors contribute to this phenomenon, including increased activity, bone weakness during growth spurts (more porous bones), and less technical control over sports activities. The majority of sports-related fractures in adolescents are low-energy injuries, which predominantly occur in males and mainly affect the upper limbs (85%) [13].

Soccer, basketball, rugby, and skiing are the main sports associated with fractures. Common fractures in adolescents involve the phalanges of the fingers, the distal radius and ulna, the metacarpals, the clavicle, the ankle, the tibial and fibular shafts, and the metatarsals. In particular, the wrist and hand are frequently affected, with the highest overall incidence observed in the phalanges, especially the proximal phalanges of the fifth finger and thumb [13].

Distal radius and scaphoid fractures are the most frequent wrist fractures, typically resulting from falls on an

outstretched hand. Clavicle fractures, which are also common, usually occur from falls on the shoulder, with approximately 90% of these fractures occurring in the middle shaft (Fig. 1).

Pelvic and lower limb fractures typically result from high-impact trauma, as observed in skiing [13].

Treatment generally remains conservative. Surgical intervention is reserved for displaced fractures, comminuted fractures, or unstable joint fractures.

The initial diagnosis and follow-up of fractures are performed using radiographs, requiring at least two orthogonal projections. In cases of diagnostic uncertainty, computed tomography (CT) or magnetic resonance imaging (MRI) offer greater diagnostic accuracy for occult fractures. The primary indications for CT include diagnosing occult fractures, evaluating complex or articular fractures where surgery is considered, and monitoring healing [19, 20].

### Growth plate fractures

The growth plate, or physis, represents the weakest part of the bone unit, especially in the zone of provisional calcification, in the transition between the physal cartilage and metaphysis. This vulnerability, and consequently the incidence of injuries, increases during adolescent growth spurts [20].

Sport-related physal fractures most commonly affect the distal ends of the femur and tibia. Due to the development of bony bridges, these physal injuries can lead to complications such as growth arrest and angular deformity [19–21].

Posttraumatic growth arrest depends more on the specific anatomical location than on the type of Salter–Harris fracture (Fig. 2). Physal fractures in the lower extremities and those involving undulating physes are most susceptible to these complications (distal femur, distal and proximal tibia) [20].



**Fig. 1** An anteroposterior radiograph of the clavicle reveals a displaced midshaft fracture (arrow) in a 14-year-old male rugby player

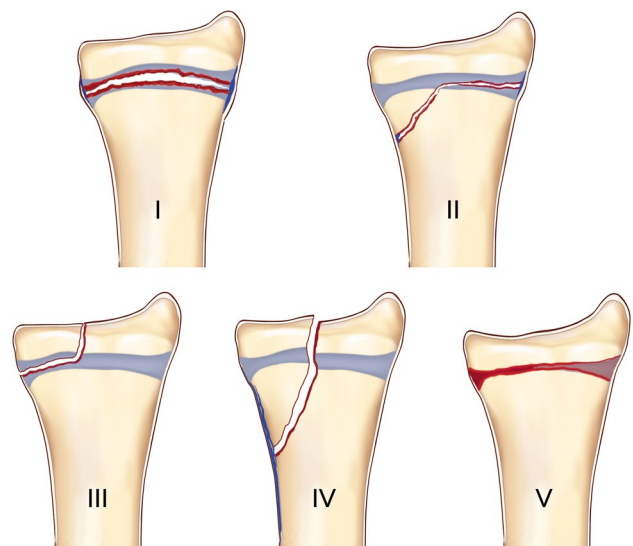
Physal fractures are often radiographically occult. MRI is the modality of choice when a growth plate fracture is suspected, by which the lesion is accurately localized, and its extent is determined (Fig. 3). Nondisplaced physal injuries show widening of the physis with increased fluid signals and perichondral rupture. The detached periosteum can become trapped within the injury zone of the physis, preventing proper closed reduction (Fig. 4). MRI and CT are also helpful for the presurgical assessment of bony bridges [19–21].

Focal periphyseal edema zones are frequently observed in MRI studies of the knees of adolescent athletes during the early stages of physiological physal fusion [22]. Focal bone marrow edema on both margins of the central portion of the closing physis is observed. These lesions, which can be responsible for the patient's pain, should not be mistaken for traumatic physal injuries and do not require follow-up.

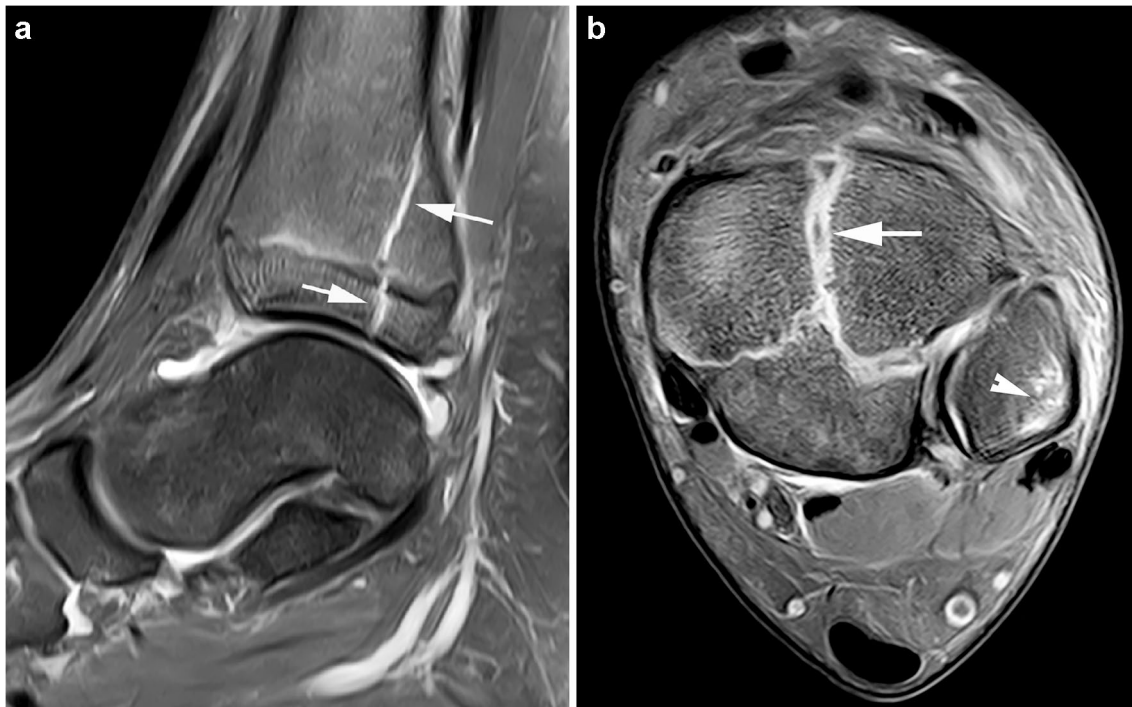
### Primary periphyseal stress injury

Primary periphyseal stress injury is the recommended term for stress-related injuries that affect one or more components of the epiphyseal-physal-metaphyseal complex [23].

Primary periphyseal stress injuries result from repetitive loading of the primary growth plate. This process initially alters metaphyseal perfusion, affecting endochondral ossification. Subsequently, the growth plate widens due to decreased apoptosis of hypertrophied chondrocytes in the hypertrophic

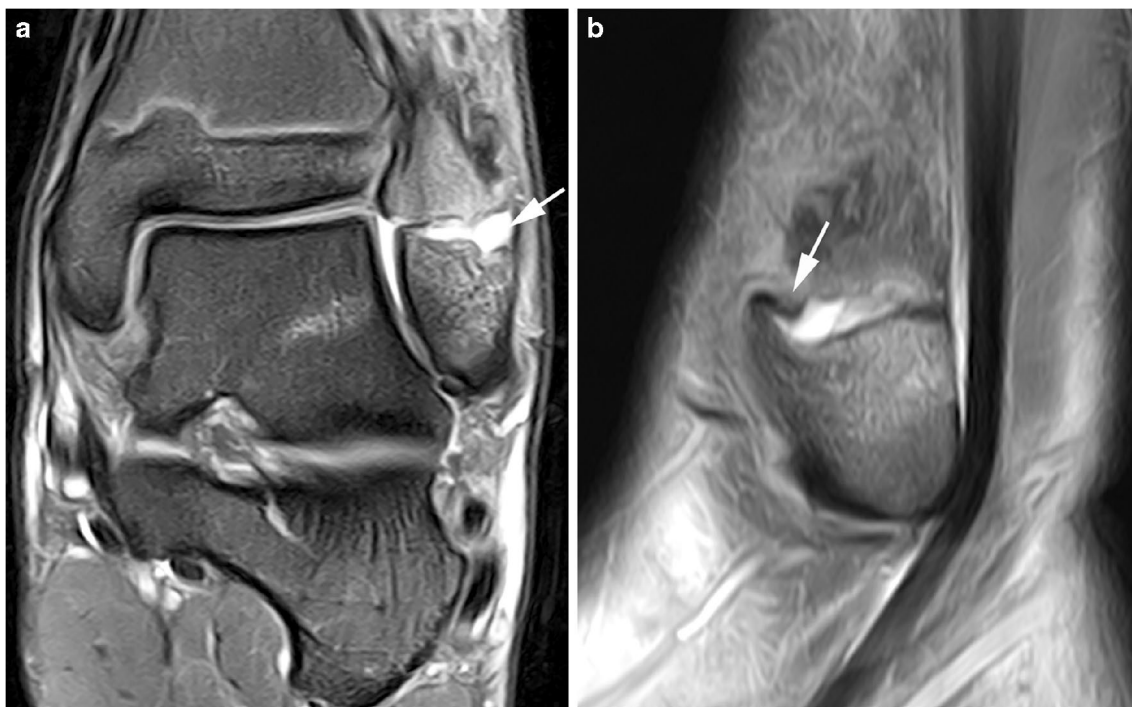


**Fig. 2** Salter–Harris fracture classification. Diagram illustrates the five types of growth plate fracture: type I involves only the physis, often presenting with widening or displacement; type II, the most common type, consists of a fracture extending through the physis and into the metaphysis; type III, an intra-articular fracture, extends from the physis through the epiphysis; type IV fracture crosses through the physis through the epiphysis; and type V, characterized by a compression injury to the physis



**Fig. 3** Proton density fat-suppressed magnetic resonance images of the ankle in a 15-year-old male soccer player. **a** Sagittal image shows a Salter-Harris type IV growth plate fracture with an oblique fracture plane traversing the epiphysis, physis, and metaphysis of the dis-

tal tibia (*arrows*). **b** Axial image reveals an anteroposterior fracture through the physis of the distal tibia (*arrow*). Note also a contusion on the lateral aspect of the lateral malleolus (*arrowhead*) and adjacent soft tissue edema



**Fig. 4** Proton density fat-suppressed magnetic resonance images of the ankle in a 14-year-old male soccer player. **a** Coronal image demonstrates a Salter-Harris type I growth plate fracture, with widening

and fluid signal on the lateral aspect of the physis of the distal fibula (*arrow*). **b** Sagittal image reveals a band of periosteum entrapped in the anterolateral margin of the physis (*arrow*)



zone and continues to expand due to active growth of chondrocytes in the germinal and proliferative zones. However, these changes are reversible if the mechanical overload is controlled, restoring normal metaphyseal perfusion [14, 18].

The most common imaging finding in primary periphyseal stress injury is physeal widening, which should not be confused with a type 1 Salter–Harris fracture, as there is no fracture plane [18]. MRI studies have shown no tissue discontinuity, displacement, or separation plane. Instead, the physeal cartilage thickens in the overloaded area, which may display irregular margins and adjacent reactive bone marrow edema (Fig. 5). This injury, which affects the proximal humerus physis, was initially described in young baseball players. It can occur in other physes, such as the wrists of gymnasts—known as “gymnast’s wrist”—or in the knees at the distal femoral or proximal tibial physes in soccer players, commonly referred to as “youth kicker’s knee” [17, 18, 23].

If the mechanical overload continues, irreversible damage to the epiphyseal-physeal-metaphyseal complex may occur, potentially leading to growth disturbances such as limb length discrepancy, angular deformity, and altered joint biomechanics [18].

### Stress fractures

Stress fractures generally occur due to fatigue caused by repetitive microtrauma that exceeds the regenerative capacity of the bone [4, 19].



**Fig. 5** Primary periphyseal stress injury in a 13-year-old male soccer player presenting with ankle pain during training. Coronal proton density fat-suppressed magnetic resonance image reveals a broad area of anterolateral physeal widening of the distal tibia (*arrows*), which is isointense compared to the rest of the physis. The images also show metaphyseal margin irregularity and peripheral bone marrow edema

Reduced muscle mass and elasticity, decreased bone mineral density, thinner cortical bones, and hormonal influences predispose the immature skeleton to stress injuries. There is a high frequency of these fractures in high-impact sports. The most common site of stress fractures in adolescent athletes is the tibia (50%) (Fig. 6). Other locations include the fibula, femur, and ankle and foot bones. Stress fractures of the upper extremities involving the phalanges and metacarpals are uncommon but have been described in high-performance tennis school players [4, 19].

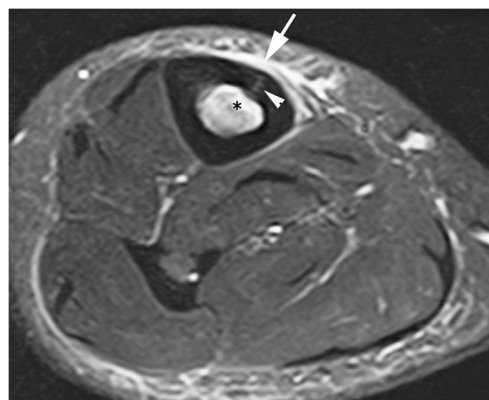
Spondylolysis is a stress fracture affecting the pars interarticularis of the neural arch (Fig. 7). It is a leading cause of lower back pain in adolescent athletes and typically occurs in males. It can progress to spondylolisthesis [24].

The most useful diagnostic method is MRI, which is very sensitive to periosteal and bone marrow edema. Stress fractures are identified as a hypointense line within the bone edema. CT with long-axis reconstructions can also easily reveal the fracture line. New CT technologies, such as spectral or photon-counting CT, can additionally show bone marrow edema, allowing for the diagnosis of both fractures and stress reactions [19].

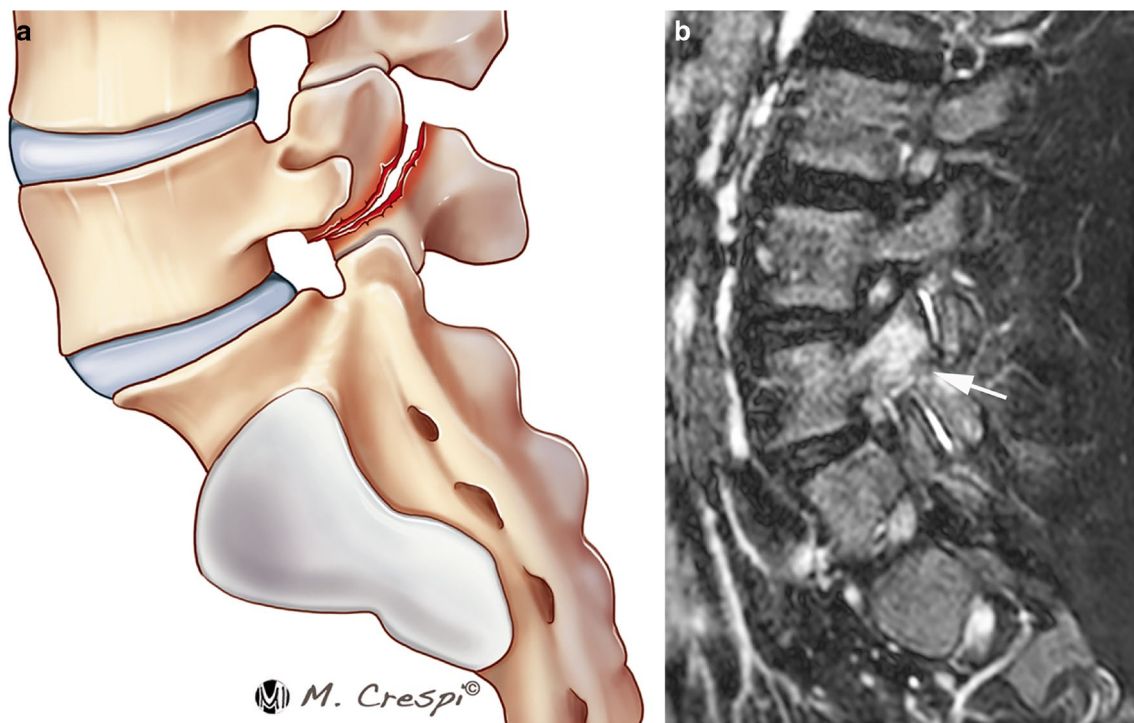
### Apophyseal injuries

The apophyses, or traction epiphyses, are secondary ossification centers that serve as tendon attachment sites. Fusion of the apophyses generally occurs in the second decade of life, often slightly later in female athletes. In adolescent athletes, the cartilage of the apophysis is weaker than that of the adjacent tendon or bone, increasing susceptibility to musculotendinous traction injuries [4, 25].

There are two main apophyseal injury patterns: chronic stress injuries—the term “apophyseal stress injury” is etiopathogenetically more appropriate than the commonly used



**Fig. 6** Medial tibial stress syndrome (shin splint) in a 17-year-old female runner. Axial short tau inversion recovery magnetic resonance image shows periosteal edema (*arrow*), incomplete intracortical fracture (*arrowhead*), and bone marrow edema (*asterisk*)



**Fig. 7** Acute spondylolysis. **a** Diagram illustrates a stress fracture located at the pars interarticularis. **b** Sagittal short tau inversion recovery magnetic resonance image in a 13-year-old male goalkeeper

with low back pain demonstrates a stress fracture through the pars interarticularis of the fourth lumbar vertebra (*arrow*)

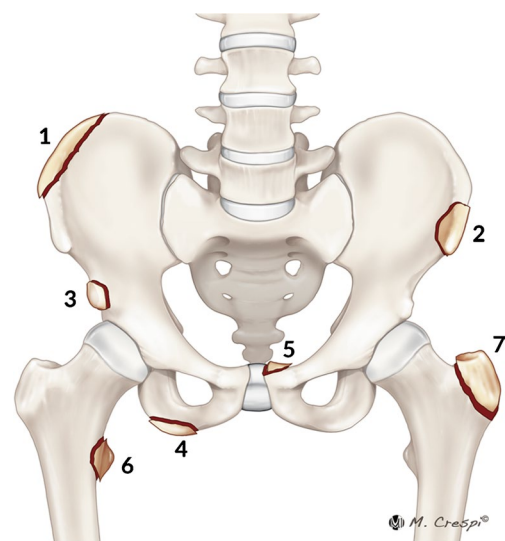
term “traction apophysitis”—and acute apophyseal avulsions due to sudden, intense muscle contractions [26, 27].

In the pelvis, apophyseal injuries are prevalent at the anterior inferior iliac spine, ischial tuberosity, and anterior superior iliac spine (Figs. 8, 9). In the knee, apophyseal stress injuries frequently occur at the tibial tuberosity (Osgood–Schlatter disease) and the inferior pole of the patella (Sinding–Larsen–Johansson disease) (Fig. 10). In contrast, knee avulsion injuries commonly involve the patellar inferior pole (patellar sleeve avulsion) [4, 25].

Other less frequent locations of apophyseal stress injuries include the medial epicondyle (Little League elbow), the base of the fifth metatarsal (Iselin disease), and the calcaneal tuberosity (Sever’s disease) [4, 12].

Clinically, patients with apophyseal stress injuries present with gradually increasing pain in the affected area without a traumatic history, which worsens with sports activities. Apophyseal avulsion fractures typically present with acute onset due to sudden muscle contractions during sports, accompanied by loss of function of the affected muscle group [27].

In apophyseal stress injuries, radiographs are usually normal or show subtle findings such as apophyseal irregularity, bone remodeling, or physseal widening. In apophyseal avulsions, the diagnosis is usually evident on radiographs unless the apophysis is not ossified (Fig. 11). Ultrasound can identify physseal widening, displacement or fragmentation,



**Fig. 8** Schema of the typical locations of pelvic apophyseal avulsion fractures and apophyseal stress injury. This diagram identifies specific anatomical sites prone to injuries, along with their associated muscle attachments: 1 iliac crest, insertions of the anterior abdominal wall muscles. 2 Anterior superior iliac spine (ASIS), insertion of sartorius and tensor fascia lata. 3 Anterior inferior iliac spine (AIIS), insertion of rectus femoris. 4 Ischial tuberosity, insertion of hamstrings muscles. 5 Superior corner of pubic symphysis, insertion of rectus abdominis. 6 Lesser trochanter, insertion of iliopsoas muscle. 7 Greater trochanter, attachment of gluteus minimus and medius



**Fig. 9** Anterior inferior iliac spine (AIIS) apophyseal stress injury in a 15-year-old male soccer player. Axial proton density weighted fat-suppressed magnetic resonance image shows focal bone marrow edema (arrows) at the AIIS without displacement and mild adjacent soft tissue edema

edema, and inflammatory changes in adjacent soft tissues, which may manifest with increased Doppler flow.

MRI is the diagnostic method of choice for suspected apophyseal injury. In early apophyseal stress injuries, characteristic findings include an increased signal in the physis

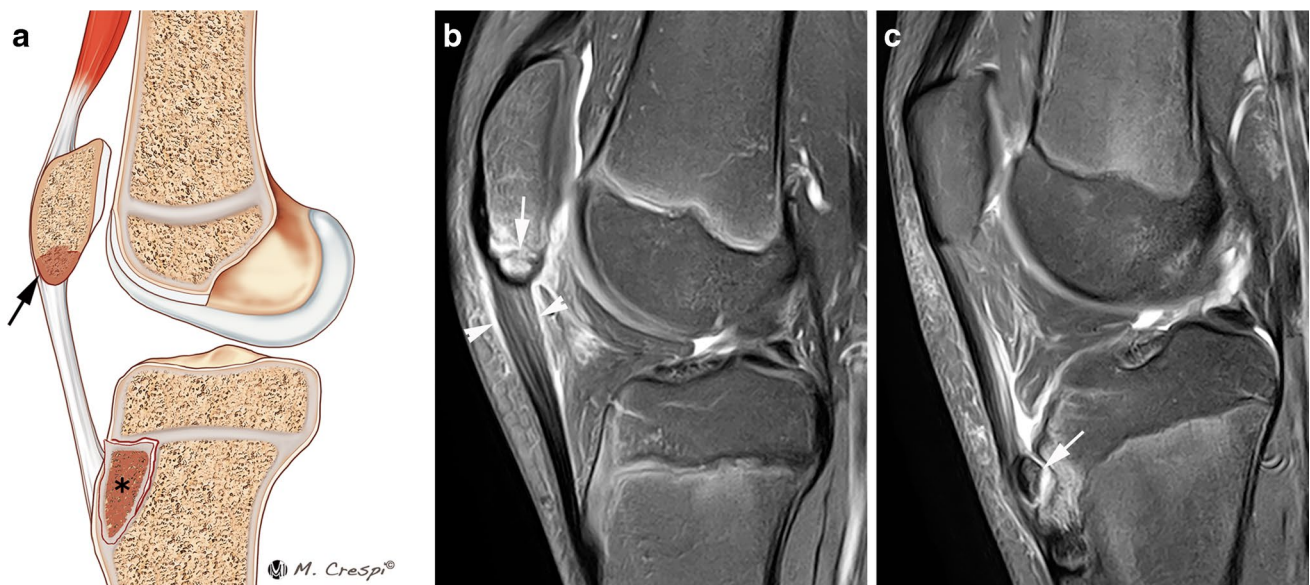
and underlying bone on T2-weighted fat-suppressed or short-tau inversion recovery (STIR) sequences [26, 27]. In more advanced stages, displacement and fragmentation of the apophysis may be observed. Delayed diagnosis is common in patients with intermittent long-standing pain. Imaging methods may reveal apophyseal fragmentation, irregular bone, and soft tissue proliferation, which should not be mistaken for malignant tumors and should not be biopsied [4, 26].

Significant complications related to chronic apophyseal injury in specific locations include the development of hamstring syndrome with sciatic nerve involvement in patients with displaced ischial tuberosity apophyseal injuries or sub-spine impingement due to a prominent anterior inferior iliac spine secondary to apophyseal injury, which can impact the distal anterior femoral neck during hip flexion [4, 26].

Treatment for nondisplaced apophyseal injuries is often conservative and involves cessation of sports activities. Apophyseal injuries that are displaced more than 2 cm may require surgical intervention. Early diagnosis and appropriate management are crucial to avoid these potential complications of apophyseal injuries [27].

### Osteochondritis dissecans

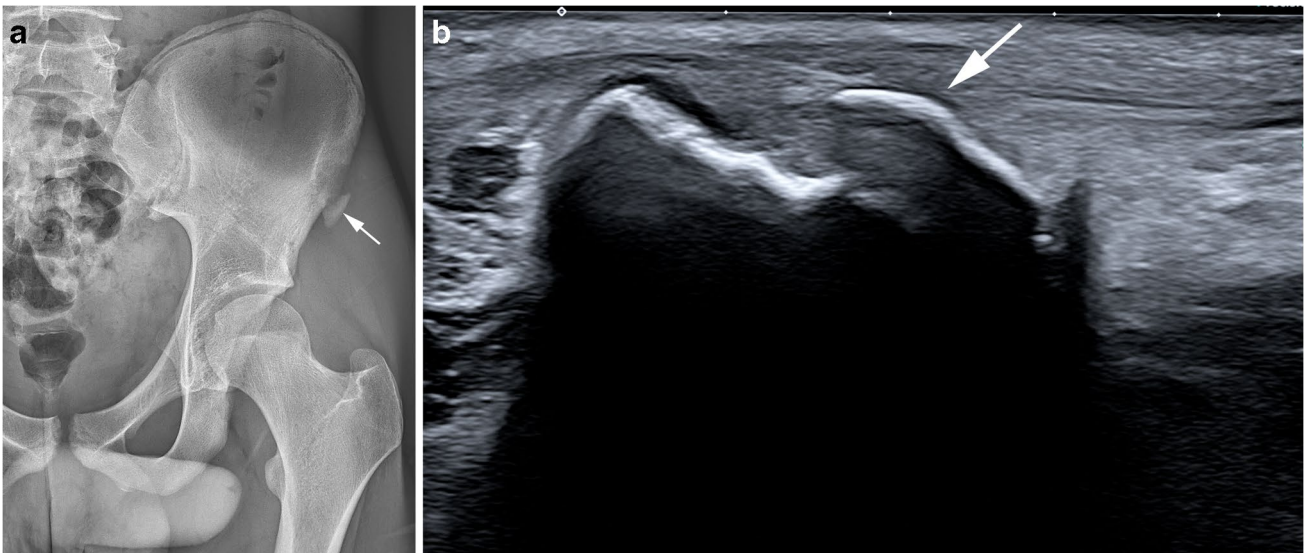
Osteochondritis dissecans (OCD) primarily affects the subchondral bone and overlying cartilage [28]. There is ongoing



**Fig. 10** Apophyseal stress injury of the anterior knee. **a** Drawing illustrating the typical findings and locations associated with Sinding-Larsen-Johansson (arrow) and Osgood-Schlatter diseases (asterisk). **b** Sinding-Larsen-Johansson disease in a 13-year-old male tennis player. Sagittal proton density weighted fat-suppressed magnetic resonance (MR) image reveals focal bone marrow edema and partial fragmentation at the inferior pole of the patella (arrow), with thickening and edema of the proximal patellar tendon (arrowheads) and peritendinous edema. **c** Osgood-Schlatter disease in a 13-year-old female basketball player. Sagittal proton density weighted fat-suppressed MR image shows bone marrow edema at the tibial tuberosity with a detached fragment (arrow), distal patellar peritendinous edema, and deep infrapatellar bursitis

ing and edema of the proximal patellar tendon (arrowheads) and peritendinous edema. **c** Osgood-Schlatter disease in a 13-year-old female basketball player. Sagittal proton density weighted fat-suppressed MR image shows bone marrow edema at the tibial tuberosity with a detached fragment (arrow), distal patellar peritendinous edema, and deep infrapatellar bursitis





**Fig. 11** Acute avulsion injury of the anterior superior iliac spine (ASIS) in a 17-year-old male soccer player. **a** Anteroposterior radiograph demonstrates a mildly displaced avulsion of the ASIS apophy-

sis (*arrow*). **b** Sagittal ultrasound image reveals an avulsion injury of the ASIS (*arrow*), involving the insertion of the sartorius and tensor fascia lata, with slight retraction

debate as to whether OCD and osteochondral lesions are distinct entities or different manifestations of the same condition, albeit with a better prognosis in adolescents. The juvenile form typically affects adolescents between 10 and 15 years of age [4, 28].

OCD has a multifactorial origin, including traumatic and mechanical overload factors [4, 28]. The most common locations in adolescent athletes are the medial femoral condyle, the talus dome, and the capitellum [4, 12, 28].

Stable OCD, with intact cartilage, typically presents clinically with nonspecific pain. In contrast, unstable lesions, which exhibit partial or complete detachment of an osteochondral fragment, are characterized by a reduced range of motion and mechanical locking, potentially increasing the risk of early osteoarthritis [4, 28].

The early stages of OCD may be radiographically occult, and radiographs are not reliable to assess stability. MRI is crucial for diagnosing and estimating the size, location, and condition of the cartilage and subchondral bone and associated injuries [28, 29] (Figs. 12, 13). MRI is also essential for postsurgical follow-up. Signs suggesting instability include a hyperintense linear signal between the fragment and the native bone on T2-weighted fat-suppressed sequences, cystic foci of 5 mm deeper than the fragment, a high signal line in the overlying cartilage, and a focal defect in the cartilage greater than 5 mm and filled with fluid [29]. Determining that a lesion is unstable typically requires combining two or more of these findings. A hyperintense interface on T2-weighted fat-suppressed sequences at the subchondral margin of the lesion is not a reliable indicator of instability

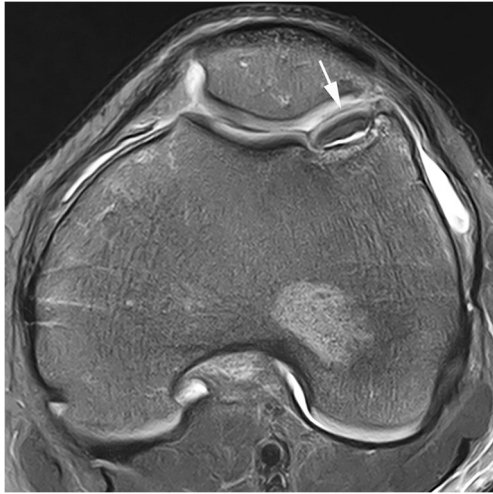


**Fig. 12** Osteochondral lesion on the medial aspect of the talar dome in an 11-year-old female soccer player. Sagittal proton density fat-suppressed magnetic resonance image illustrates an osteochondral lesion with intact cartilage over the lesion and surrounding fluid-like signal intensity (*arrows*). Note also bone marrow edema in the metaphysis of the distal tibia, related to an early phase periphyseal stress injury

on its own, as it may represent vascular granulation tissue in the healing phase [28].

Stable lesions generally respond well to conservative treatment, whereas unstable lesions, or those that do not respond to conservative management, may require surgical intervention.





**Fig. 13** Osteochondral lesion on the lateral trochlear facet with detached osteochondral fragment in a 15-year-old male tennis player. Axial proton density fat-suppressed magnetic resonance image shows an extensive osteochondral lesion with a large, detached, and unstable osteochondral fragment (*arrow*)

### Accessory ossicle syndromes and bone coalitions

Accessory ossicles are unfused secondary ossification centers located in typical anatomical sites [30]. They are characterized by smooth, well-defined cortical margins and are usually connected to adjacent bone by a synchondrosis. Numerous accessory ossicles exist throughout the skeletal system, especially in the wrist, hand, ankle, and foot.

Accessory ossicles are anatomical variants that sometimes cause painful conditions known as ossicle syndromes [4, 30]. The most common ossicle syndromes in adolescent athletes include os trigonum syndrome (often the cause of posterior ankle impingement), symptomatic accessory navicular in the ankle, symptomatic bipartite patella in the knee, and os styloideum (carpal boss) in the hand [4, 5, 30].

Ossicle syndromes typically result from injury to the ossicle synchondrosis, generally due to chronic mechanical overload or, less frequently, acute trauma during sports activities. The most common clinical presentation is posterior ankle impingement caused by microtraumatic instability of the os trigonum in sports such as soccer and basketball [4, 5, 30].

Radiographs can identify the presence of these ossicles and, in an appropriate clinical context, suggest a diagnosis. Understanding the ossicular anatomy is essential to avoid misdiagnosis as marginal fractures or bone avulsions. In advanced stages, ossicle syndromes may manifest as widening of the synchondrosis, sclerosis, or small marginal cysts [30]. Ultrasound can detect associated bone and soft tissue alterations in ossicle syndromes and guide diagnostic and therapeutic injections.

MRI is the imaging technique of choice for diagnosing ossicle syndromes [30]. MRI can show characteristic findings in the early stages, such as focal bone edema, synovitis, joint effusion, and adjacent soft tissue edema. In more advanced stages, irregularity or widening of the synchondrosis and degenerative changes at its margins, such as sclerosis and intraosseous cysts, can occur. MRI also enables the diagnosis of frequently associated lesions, such as periarticular ganglia and tendon injuries.

A coalition is an abnormal congenital union between two bones, secondary to incomplete segmentation of the tarsal or carpal bones. These unions can be fibrous (syndesmosis), cartilaginous (synchondrosis), or osseous (synostosis) [31]. The most common coalitions are calcaneonavicular and talocalcaneal coalitions in the tarsus and lunotriquetral and capitolunate coalitions in the carpus.

Bone coalitions can alter biomechanics and become symptomatic in adolescent athletes [32].

Radiographs can be used to diagnose bone coalitions. The joint space in fibrous or cartilaginous coalitions appears to be narrowed with irregular margins. The coalition may not be directly visible on radiographs of the tarsus, and specific oblique projections may be needed. Characteristic radiographic findings on the lateral view, such as the “anteater nose” sign in the calcaneonavicular coalition and the “talar beak” and “C” signs in the talocalcaneal coalition, should be considered [31].

Both CT and MRI allow for easy and precise diagnosis of coalitions. MRI is the most sensitive technique for detecting bone marrow edema in symptomatic patients [31, 32]. The treatment of bone coalitions is generally conservative. Various surgical options may be considered for refractory patients.

### Joint instability

#### Anterior shoulder instability

Anterior glenohumeral dislocation is a frequent problem in adolescent athletes. It typically results from indirect trauma to the upper extremity, with the shoulder in abduction, extension, and external rotation. It occurs in a variety of sports, with a higher incidence in handball, judo, swimming, and volleyball. There is a significant male predominance in late adolescence (14–19 years). Recurrent dislocation is a significant issue, especially in late adolescence, with recurrence rates of up to 80% [33].

Anterior dislocation of the humeral head causes a spectrum of injuries beginning with the avulsion of the anterior band of the inferior glenohumeral ligament and its insertion in the anteroinferior labrum (Bankart lesion and its variants) [33, 34] (Fig. 14). Subsequently, there is an impact between

the posterosuperior aspect of the humeral head and the anteroinferior glenoid margin. This impact usually causes an impaction fracture on the posterosuperior margin of the humeral head (a Hill-Sachs lesion) and, occasionally, a fracture of the anteroinferior glenoid margin (a bony Bankart lesion) [33, 35].

A Hill-Sachs lesion is considered an unstable (“off-track”) bony defect when it exceeds 83% of the anteroposterior diameter of the glenoid cavity. Anteroinferior glenoid margin defects are considered critical when they exceed 25% of this diameter. Additionally, a bipolar bony defect, which combines both bony Bankart and Hill-Sachs lesions, is also common [35].

CT is the most helpful technique for precisely quantifying bony defects [35]. MR arthrography is the imaging method of choice for evaluating glenohumeral instability, as it allows for an accurate assessment of capsulolabral lesions, bony defects, and associated injuries [33].

Surgical treatment, either arthroscopic or open, should be performed primarily based on the extent of bony defects in patients with recurrent instability or functional limitations.

### Lateral patellar dislocation

Lateral patellar dislocation frequently occurs during sports activities (60%) and is most common in females during the second decade of life. It is typically the result of an external rotation movement, with the knee in flexion and the foot

fixed. The patella usually reduces spontaneously when the knee is extended after the injury [36].

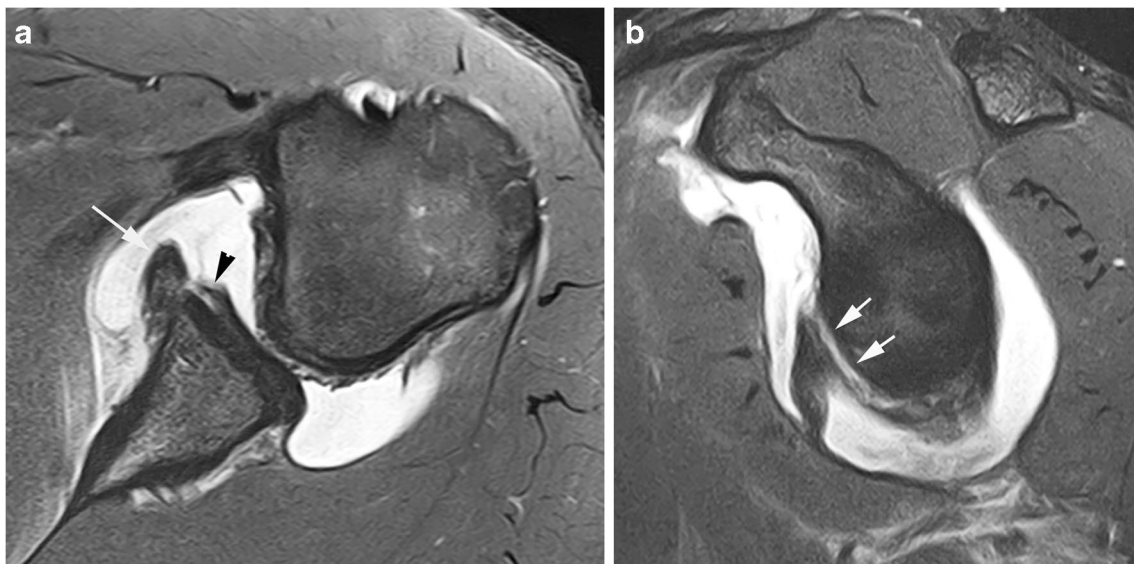
Several anatomical abnormalities associated with femoropatellar dysfunction are risk factors for recurrent patellar dislocation, including trochlear dysplasia, patella alta, and Wiberg type 3 patella [36, 37]. The dislocation causes varying degrees of injury to the medial patellofemoral ligament (MPFL) and an impact of the medial patellar margin with the anterolateral aspect of the lateral femoral condyle, leading to bone contusions or osteochondral fractures [10, 38] (Fig. 15). Sometimes, chondral delamination of the patella occurs, which has a poor prognosis. The recurrence rate of patellar dislocation is high (15–50%).

CT allows the evaluation of the femoropatellar joint and predisposing factors, which is particularly useful in patients considered for surgery. MRI reveals secondary alterations due to patellar dislocation, including the degree of injury and location of the MPFL, bone contusions or fractures at the medial patellar margin and anterior margin of the lateral femoral condyle, and the articular cartilage status [10, 37, 38].

### Ligamentous lesions

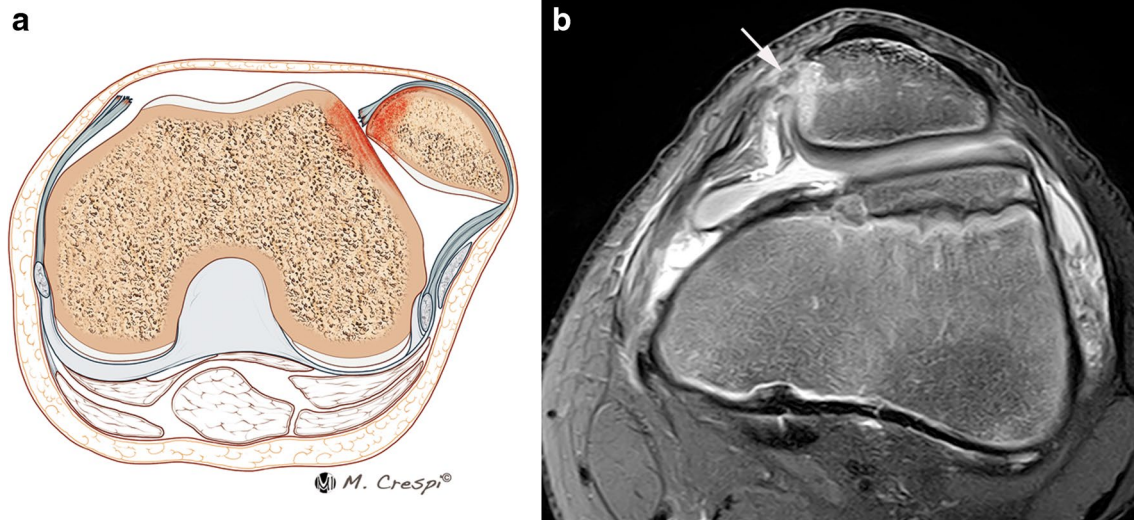
#### Anterior cruciate ligament injuries

Anterior cruciate ligament (ACL) injuries are a significant concern in adolescent athletes, particularly among females [10, 11, 39]. Most ACL injuries in adolescent athletes occur without contact and during deceleration to initiate cutting or



**Fig. 14** Acute anterior glenohumeral dislocation in a 16-year-old male surfer due to sudden abduction and external rotation trauma. Axial (**a**) and coronal (**b**) proton density fat-suppressed magnetic resonance images display a Bankart tear (*arrows*) with anteroinferior

periosteal detachment (ALPSA variant of Bankart lesion) and anteroinferior marginal chondral delamination in the glenoid cavity (*arrowhead* in **a**). Note that the presence of hemarthrosis produces an arthrographic effect in acute dislocations



**Fig. 15** Acute lateral patellar dislocation. **a** Diagram illustrates the characteristic injury spectrum of lateral patellar dislocation: tear of the medial patellofemoral ligament and bone contusions on the medial edge of the patella and the anterolateral margin of the lateral femoral condyle (“kissing lesions”). **b** Axial proton density fat-

suppressed magnetic resonance image in a 12-year-old female soccer player showing complete rupture of the patellar insertion of the medial patellofemoral ligament (*arrow*) and bone contusions on the medial edge of the patella

pivoting movements. A torn ACL results in anterior tibial translation, impacting the anterior margin of the lateral femoral condyle and the posterolateral tibial plateau, potentially causing bone contusions or impaction fractures [10, 39].

Soccer has the highest rate of ACL tears, with injuries occurring eight times more often during matches than during training. Adolescent female soccer players are two to eight times more susceptible to this injury. Various anatomical, biomechanical, and physiological differences in adolescent females contribute to this predisposition. Females have shorter and smaller limbs relative to body size, wider pelvises, and a greater  $Q$  angle, increasing the lateral force of the quadriceps on the patella. Additionally, females exhibit more significant joint laxity and different muscle activation patterns [10, 11].

MRI is the imaging method for diagnosis [10, 40, 41]. The findings include loss of continuity and displacement of ligament fibers, thickening, and increased intraligamentous signals (Fig. 16). Indirect signs include bone contusions or impaction fractures of the lateral femoral condyle and posterolateral tibial plateau (“pivot shift”) [10, 41]. Partial tears are also common in adolescent patients. MRI can be used to precisely determine the extent and bundles affected. Three-dimensional sequences or high-resolution oblique coronal slices oriented to the ACL are helpful in these cases.

Surgical treatment for ACL injuries in adolescent athletes is recommended to maintain activity levels and prevent joint damage.

### Anterior cruciate ligament avulsion injuries

ACL avulsion injuries are more frequent in early childhood and adolescence (8–14 years) than in older patients due to the weaker immature chondro-osseous junction, especially at the tibial insertion of the ACL [26, 42] (Fig. 17). These injuries generally occur through mechanisms similar to those of ACL tears.

Classification systems based on MRI findings consider displacement (less than or more than 2 mm), entrapment of the intermeniscal ligament or anterior horns of the menisci in the fracture site, and associated injuries (meniscal and chondral injuries) [10, 26, 42].

Nondisplaced fractures are treated with immobilization. Displaced fractures, those with interposed soft tissues, or associated injuries should be repaired.

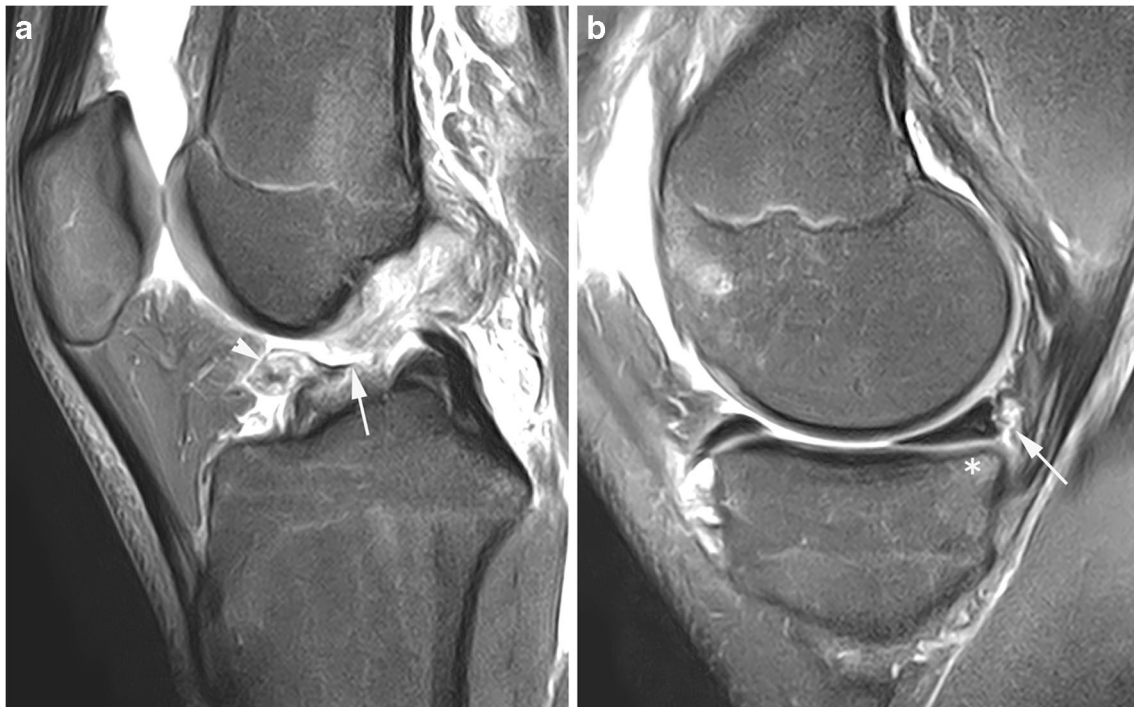
### Ankle sprains

Ankle sprains are the most common injuries in sports practice, with up to 85% affecting the lateral ligament complex. Most ankle sprains respond to conservative treatment. However, 20–30% of patients may develop chronic pain and ankle instability [43].

Recently, new concepts have emerged based on advancements in arthroscopy, such as microinstability and rotational instability of the ankle [43].

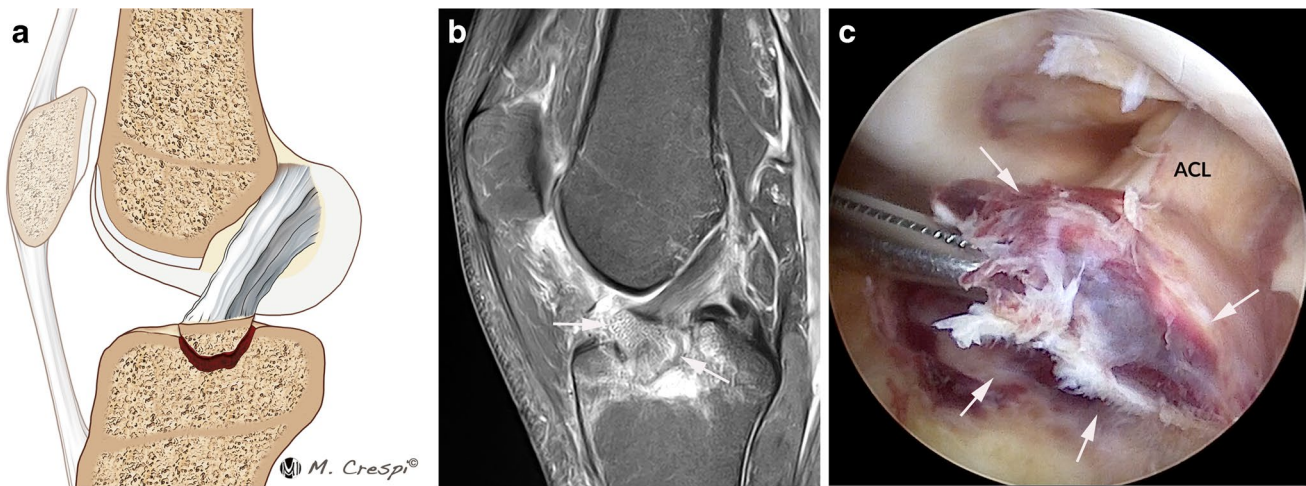
Chronic lateral ankle instability is associated with deltoid complex injuries in up to 40% of cases. Secondary medial





**Fig. 16** Sagittal proton density fat-suppressed magnetic resonance images of the knee in a 16-year-old female soccer player. **a** Shows an acute complete tear of the anterior cruciate ligament (*arrow*) with the distal stump folded anteriorly (*arrowhead*). Moderate hemarthrosis is

present. **b** Shows a meniscotibial ligament tear (type 3B ramp lesion) (*arrow*). Focal edema on the adjacent posterior margin of the medial tibial plateau (“shiny corner”) is an indirect marker of meniscal injury (*asterisk*)



**Fig. 17** Anterior cruciate ligament (ACL) avulsion fracture at the tibial insertion. **a** Drawing illustrates an avulsion injury at the tibial attachment of the ACL. **b** ACL avulsion fracture in a 16-year-old male soccer player. Sagittal proton density fat-suppressed magnetic

resonance image shows an ACL avulsion fracture at the tibial insertion (*arrows*) with elevation of the superior margin. **c** Arthroscopic correlation image demonstrates the ACL avulsion fracture (*arrows*)

and lateral chronic instability can lead to “rotational instability of the ankle,” with significant prognostic and therapeutic implications [43]. Although less common than lateral instability, medial ankle instability and syndesmotic instability

are important pathological conditions. They often result from severe injuries to the medial or syndesmotic ligament complexes and are usually associated with multiligamentous injuries and ankle fractures.

Ultrasound allows for the precise diagnosis of ligament injuries in the lateral, deltoid, and syndesmotic complexes of the ankle while also assessing the tendon structures, retinacula, avulsions, and occult fractures [10, 43].

MRI and MR arthrography can be helpful in accurately diagnosing ligament injuries and associated lesions, especially in patients with persistent pain or recurrent instability, facilitating an appropriate therapeutic approach [43].

### Tendinous injuries

Tendinous injuries are uncommon in adolescent athletes and primarily affect those in late adolescence with greater skeletal maturity. Tendinopathies prevalent in adults are rare in adolescent athletes [5]. For instance, rotator cuff tendinopathy in adolescents should prompt consideration of underlying glenohumeral microinstability [34]. Rotator cuff tears are usually traumatic and generally limited to partial tears of the articular surface. The most frequent tendinopathies are patellar tendinopathy (jumper's knee) and Achilles tendinopathy. Recently, the role of the so-called PLAC complex (pyramidalis–anterior pubic ligament–adductor longus complex) has gained relevance in the understanding of groin pain [44]. Ultrasound is the most helpful method for assessing superficial tendinous pathology, with Doppler studies demonstrating increased intra- and peritendinous vascularization. It also has the advantage of dynamic evaluation. MRI is suitable for assessing deep tendinous lesions, such as those involving the PLAC complex [44].

### Meniscal injuries

Meniscal injuries are less prevalent in adolescents [45]. Meniscal tears are most common in sports such as soccer, basketball, and skiing.

The International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) classification introduces a system that facilitates unified terminology and communication between radiologists and orthopedic surgeons. Tear patterns are classified into six categories: longitudinal (which can extend to a bucket-handle tear), radial, radial flap, horizontal flap, horizontal (usually degenerative but can be traumatic in adolescents), and complex (involving more than one tear pattern). This classification also includes the following specific tears requiring special attention: meniscal root and meniscocapsular injuries (ramp and Wrisberg rip lesions) [45, 46].

In adolescent athletes, 70% of meniscal injuries affect the medial meniscus, with peripheral longitudinal and radial tears being the most common. Bucket-handle tears are also frequent. Similar to those in adults, ramp and Wrisberg lesions are commonly observed with ACL tears [47] (Fig. 16).

A discoid meniscus is an anatomical variant characterized by an excessively wide body, typically involving the lateral meniscus (1–5%). A discoid meniscus is frequently associated with intrasubstantial degenerative changes and complex or bucket-handle tears [26]. The hypermobile lateral meniscus is a rare clinical entity characterized by lateral joint line pain and locking during flexion, secondary to posterior horn instability due to injury of the popliteomeniscal ligaments [48].

MRI is the modality of choice for diagnosing meniscal injuries [45, 46]. Assessment in all three MRI planes is crucial, with particular importance on the axial plane to define the pattern and extent of radial and longitudinal tears. MRI should describe meniscal tear patterns following the ISAKOS classification and pay special attention to areas difficult to visualize with arthroscopy; these patterns include ramp lesions, Wrisberg rips, and posterior meniscal roots.

### Hip labral injuries

Traumatic labral tears are uncommon in adolescent athletes. They occasionally occur in sports such as soccer and involve constant pivoting movements with a weight-bearing femur. Most labral injuries occur in the context of femoroacetabular impingement (FAI) syndrome or hip dysplasia [49, 50].

FAI is a clinical entity associated with morphological abnormalities of the femur and/or acetabulum. When combined with extreme hip movements in flexion, adduction, and internal rotation, these abnormalities lead to repetitive impingement, potentially causing labral and/or chondral damage [49, 50].

There are three types of FAI: cam type (focal bony prominence at the femoral head–neck junction), pincer type (acetabular overcoverage), and mixed type (a combination of both) [50].

Cam-type FAI is more common in males, whereas pincer and mixed types are more prevalent in females. FAI primarily affects young adults but is increasingly common in adolescent athletes, particularly the cam type. Cam deformity in adolescent athletes, associated with increased training during growth spurts, gradually develops from age 13 years until growth plate closure [51].

Patients with cam-type FAI exhibit a specific pattern of labral and articular cartilage damage. Initially, impingement causes injury at the chondrolabral junction, progressing to detachment of the articular cartilage from the periphery to the center (tangential “outside-in” shear forces), resulting in large acetabular cartilage delaminations (“carpet lesions”) [50]. A common anatomical variant that should not be confused with chondrolabral detachment is the sublabral sulcus, which is typically located in the posterosuperior quadrant. The sublabral sulcus has well-defined margins with no intrasubstance changes in the labrum or adjacent cartilage.

In contrast, chondrolabral detachment usually occurs in the anterosuperior quadrant, presenting with some margin irregularity and often associated with chondral lesions [50].

Clinical manifestations of hip dysplasia and FAI generally occur in young adult athletes and are less common during adolescence.

Labral tears can be reliably assessed with MRI using a unilateral hip protocol. However, the ability of MRI to accurately evaluate chondral lesions, a major prognostic factor, is limited. The reference diagnostic imaging test is MRI arthrography with axial traction, which allows for the assessment of labral tears and chondral lesions with diagnostic efficacy exceeding 95% [50].

Treatment for chondrolabral injuries detected via MRI should only be considered when clinical symptoms are present. Hip arthroscopy has been reliably used for the surgical treatment of hip labrum injuries and FAI, yielding excellent results in adolescent athletes. Surgical treatment of hip labral tears in adolescents may involve repair or reconstruction. Bone deformities associated with FAI should also be corrected during the arthroscopic procedure.

## Muscle injuries

The increasing involvement of adolescent athletes in professional training and competition programs, especially in soccer, combined with a developing muscular system, are critical factors in the increase in these types of injuries [52]. Muscle injuries are more common in adolescent males, although females have a greater incidence of quadriceps injuries [10].

The injury mechanism is typically an indirect stretching mechanism. The most frequently affected muscle groups are

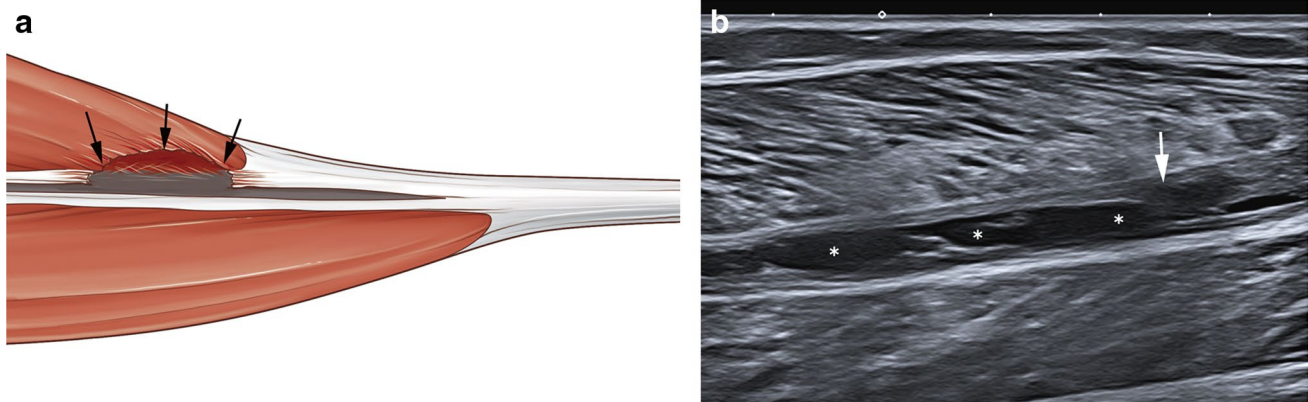
the quadriceps (primarily the rectus femoris), hamstrings, and triceps surae [10, 52].

Various classification systems exist for muscle injuries, with the British Athletics Muscle Injury Classification [53] based on MRI being the most widely used. Both ultrasound and MRI play essential roles in the diagnosis, management, follow-up, and safe return to play for these patients [52] (Fig. 18).

Muscle injuries are generally treated conservatively, although complete tears or avulsions may require surgical repair.

## Conclusion

Sports injuries in adolescents are a growing concern, driven by multiple risk factors, including increased sports activity and training intensity, which place repetitive strain on an immature skeleton. The incidence of these injuries is notably greater in female adolescent athletes due to anatomical factors, making them more prone to high-prevalence injuries such as ACL tears, especially in soccer players. Additionally, excessive training during a growth spurt can lead to conditions such as cam morphology of the femoral neck, predisposing individuals to femoroacetabular impingement. Sports injuries and complications can significantly impact the future sports performance of adolescent athletes. Imaging methods, particularly ultrasound and MRI, are crucial for diagnosis and treatment planning. By implementing comprehensive injury prevention strategies and advanced imaging techniques, we can better manage and mitigate the impact of sports injuries on adolescent athletes.



**Fig. 18** Acute gastrocnemius muscle injury grade 2C British Athletics Muscle Injury Classification [53]. **a** Drawing illustrating an acute medial gastrocnemius aponeurosis injury (arrows). **b** Sagittal ultra-

sound image of a 16-year-old male soccer player shows a myoaponeurotic tear of the medial gastrocnemius with focal aponeurotic defect (arrow) and intermuscular hematoma (asterisks)



**Author contribution** Concept of the article: Ce.A. and C.L.  
 Collected and analyzed data: Ce.A., C.A., C.L., and R.D.  
 Drafted the initial manuscript: Ce.A. and C.L.  
 All authors have reviewed and approved the final submitted manuscript.

## Declarations

**Conflicts of interest** None

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