PICTORIAL ESSAY Musculoskeletal Imaging

Imaging of traumatic injuries of the paediatric pelvis and hip

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ABSTRACT

Trauma to the paediatric hip and pelvis may cause a diverse group of acute and chronic traumatic conditions characterised by significant variations in incidence and severity. Knowledge of the morphologic and biomechanical peculiarities of the developing pelvis constitutes an essential background for understanding paediatric pelvic trauma. Imaging studies should follow a thorough clinical examination and clearly play an integral role in the assessment and management of pelvic injuries in children. The choice of the most appropriate imaging modality and accurate interpretation of imaging findings are crucial for reaching the correct diagnosis without delaying management. This pictorial essay focuses on the various causes of trauma-related hip and pelvic pain in the paediatric population. Special attention is given on pathophysiologic mechanisms, appropriate imaging work-up and imaging findings indicative of various types of this diverse group of injuries.

KEY WORDS

Pelvic injuries; hip injuries; childhood; sports injuries/imaging; trauma

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1. Introduction

Pelvic and hip fractures in children are uncommon and related to acute high-energy trauma. Prompt diagnosis is of outmost importance due to their association with multisystem injuries [1, 2]. Increased interest in sports and physical fitness has broadened the spectrum of trauma-related painful syndromes around the pelvis in children and adolescents. Apophyseal avulsions and stress fractures or reactions represent the most frequently encountered skeletal injuries [3, 4] whereas contusions and musculo-tendinous sprains are the most common soft tissue lesions about the hip and pelvis [5]. Due to better understanding of hip and pelvis biomechanics, impingement syndromes are currently diagnosed with increased frequency in younger patients. Importantly, in children with hip pain and a history of trauma, a high index of suspicion for potential non-traumatic disease may impede misdiagnosis.

In depth understanding of morphologic and biomechanical peculiarities of the immature paediatric pelvis is of paramount importance when taking care of children with suspected pelvic injury. Familiarity with the spectrum of imaging findings in various imaging modalities allows optimal depiction and characterisation of pathology and ensures timely diagnosis. In this setting, detailed medical history and clinical examination are imperative for guiding the radiological investigation towards the appropriate direction. The age and level of physical activity of the child further helps to narrow the differential diagnosis. This pictorial essay aims to provide updated data on the various causes of hip and pelvic trauma-related musculoskeletal pain in the paediatric population. Special attention is given on pathophysiologic mechanisms, appropriate imaging work-up and imaging findings indicative of various types of injuries.

2. Anatomical considerations in the growing pelvis

The pelvis arises from three primary ossification centers: the ilium, ischium, and pubis [6]. These ossification centers merge at the triradiate cartilage and fuse between 16 and 18 years (**Fig. 1**). The ischium and pubis meet at the inferior pubic ramus and usually fuse at 6-7 years of age; however fusion may occur as early as 4 years [6]. The most important secondary ossification centers around the pelvis include the iliac crest, ischial apophysis, anterior superior iliac spine and anterior inferior iliac spine. Additional secondary centers occur at the pubic tubercle, angle of pubis and lateral sacral wing (**Fig. 2**) [7]. The iliac crest ossification center is

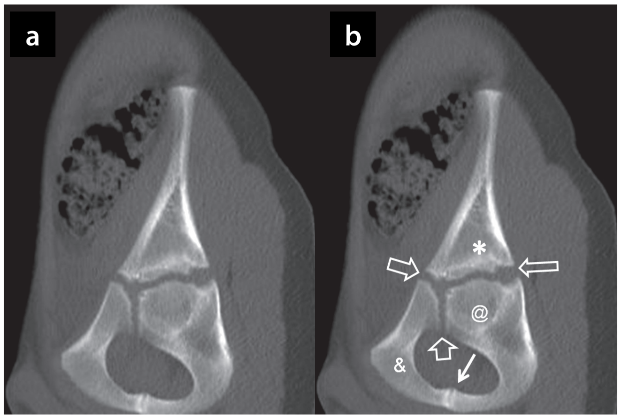

Fig. 1. *Sagittal CT reconstruction of the pelvis in a 10-year-old boy* ***(a)*** *and respective annotated image* ***(b).*** *The three pelvic bones, ilium (*), ischium (@), and pubis (&) are shown. The "T" shaped lucent area represents the triradiate cartilage, where the three ossification centers merge (open arrows). The ischiopubic ramus, where the pubis meets the ischium (arrow) shows more advanced fusion compared to the triradiate cartilage.*

the first to appear, at 13-15 years, and fuses between 15 and 17 years. The secondary ossification center of the ischium is first seen at 15-17 years and fuses at 19 years; however this process may last until 25 years of age. The ossification center in the anterior inferior iliac spine may appear between 13 and 15 years and fuses by 18 years of age [6, 7]. Acetabular development is complex. The triradiate cartilage and cartilaginous periphery are the two sites of primary growth and remodeling which ensure that the diameter and depth of the acetabulum develops proportionally with the growing femoral head [8]. Osseous maturation in the triradiate cartilage allows the pubis, ischium and ilium to enlarge and the acetabulum to expand. On another direction, appositional growth of its periphery together with marginal periosteal new bone formation at the acetabular rim account for an increase in acetabular depth. Three secondary ossification centers arise in the hyaline cartilage surrounding the acetabulum (**Fig. 1**). The os acetabuli, representing the epiphysis of the pubis, contributes to anterior acetabular wall development, is the largest secondary center, appears at the age of 8 years and unites with the pubis by 18 years of age. The acetabular epiphysis represents the epiphysis of the ilium, forms a significant portion of the superior acetabular wall and joint surface, and its development and fusion parallel that of os acetabuli. The third and smallest center, the secondary center of the ischium, is rarely seen, has a minor contribution to acetabular development, appears at 9

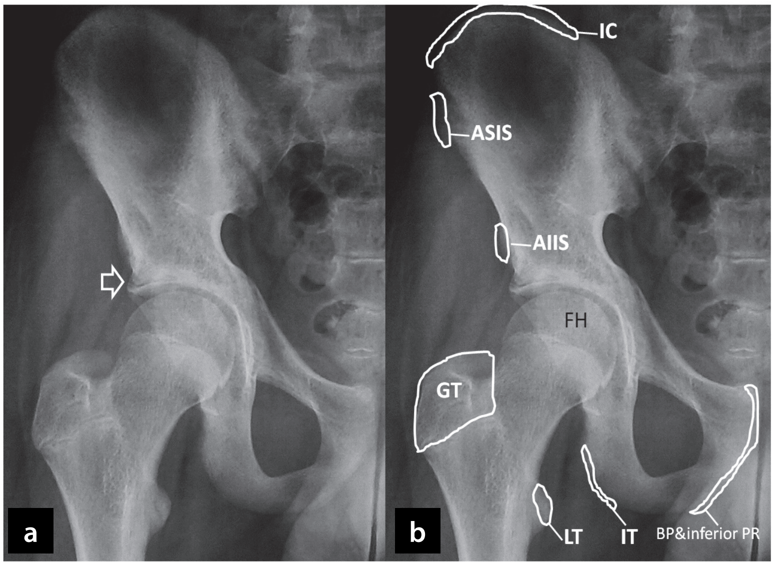

*Fig. 2. Anteroposterior radiograph of the pelvis in a 15-year old male **(a)** and respective annotated image **(b)**. Apophyseal sites in the pelvis and proximal femur. IC: area of iliac crest (abdominal muscles insertion). ASIS: Anterior superior iliac spine (Sartorius, fasciae latae insertion). AIIS: Anterior inferior iliac spine (rectus femoris insertion). GT: Greater trochanter (Hip rotators insertion). LT: Lesser trochanter (iliopsoas insertion). IT: Ischial tuberosity (Hamstrings insertion). BP: Body of pubis and PR: pubic rami (adductors and gracillis insertions). Note unfused ossification center of the acetabulum (arrow), not to be confused with fracture. FH: Epiphysis of femoral head.*

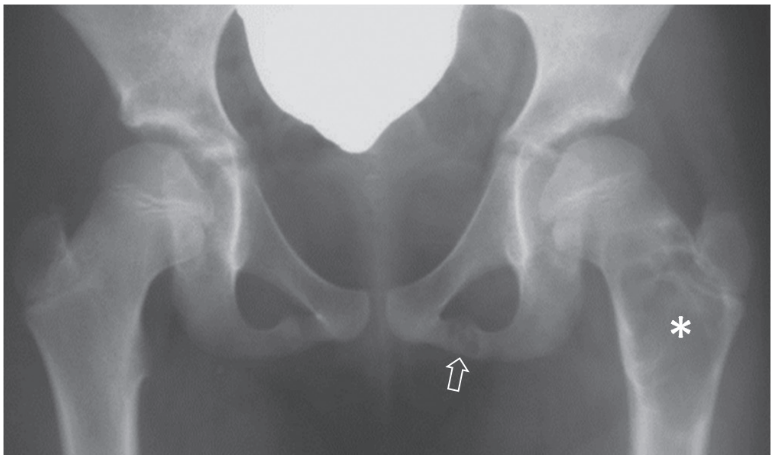

Fig. 3. Anteroposterior radiograph of the pelvis in a 8-year old female with a left femoral aneurysmal bone cyst (*). Unossified left ischiopubic synchondrosis (arrow) should not be interpreted as a lesion.

years and fuses with the acetabulum by 17 years of age [8].

The proximal femur has two secondary ossification centers, which appear in the same cartilaginous mass: the femoral capital epiphysis and the greater trochanter. The ossification center of the femoral head appears radiographically at a mean age of approximately 4 months in girls and 4.5 months in boys, while it is nearly always present by the age of 6 months [9]. Femoral head ossification center may be ultrasonographically visible in as early as 2 weeks of age, and usually appears around 2-3 months [10]. The ossification center of the greater trochanter appears at a mean age of 2.5 years in girls and 3.5 years in boys [9]. Both ossification centers provide longitudinal growth to the femur as they interact to determine proximal femoral growth and the angle of the femoral neck. Closure of the capital physis follows fusion of the trochanteric ossification center with the femoral shaft/neck, begins superolaterally, progresses inferiomedially and is completed in half of females by 14 years and in half of males by 17 years [11].

3. Normal variants

Radiographic normal variants unique to the developing pelvis should not be interpreted as pathology and include:

Ischiopubic synchondrosis: It is the fusion site between the pubis and ischium, which can occur at any age between 4 years and puberty, usually around 6-7 years. Before fusion, the synchondrosis enlarges and appears osteopenic due to uneven mineralisation [12]. This appearance may be unilateral or bilateral and simulate fractures or osteolytic processes (**Fig. 3**).

Apophyses: Variations in normal apophyses may mimic avulsion fractures or apophysitis. Minor irregularities in the outline of the acetabulum, iliac crest and pubic bones at the symphysis are commonly encountered between 3 years

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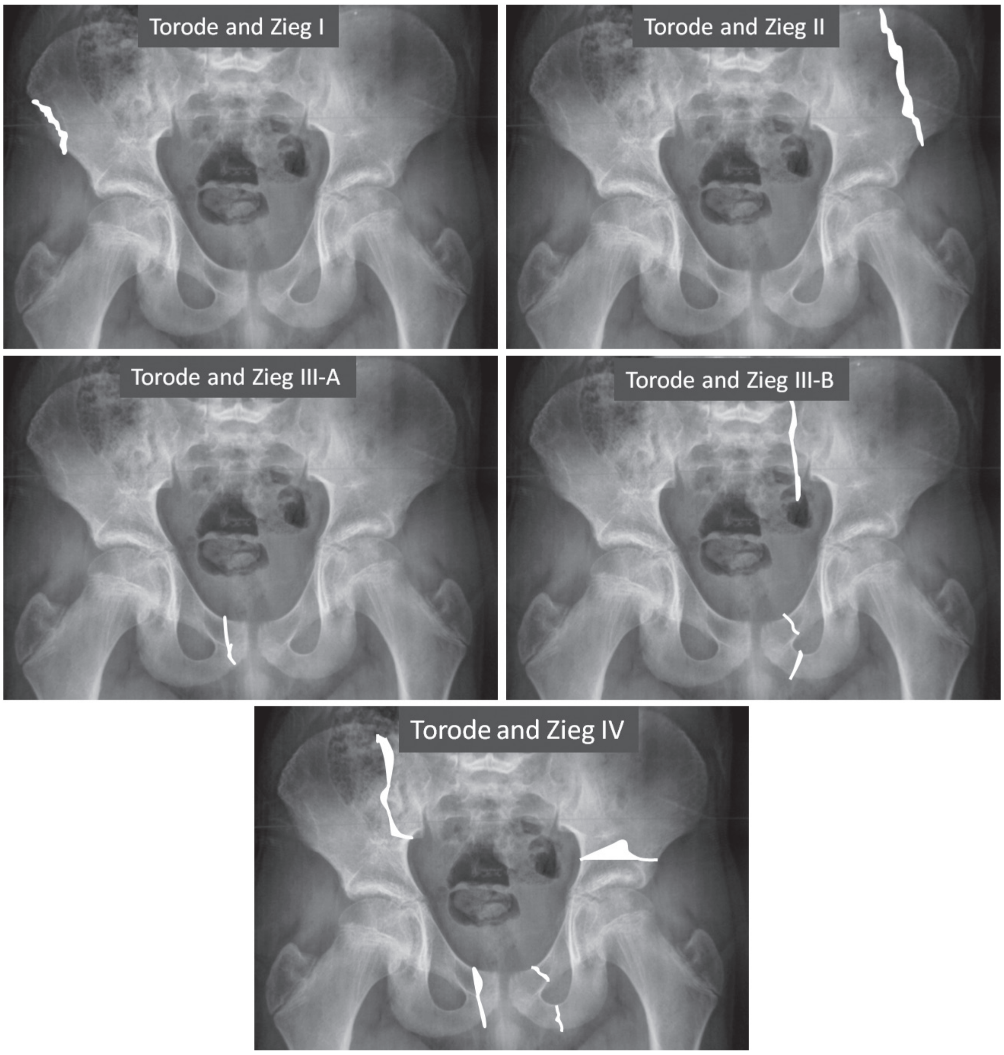

Fig. 4. *Modified Torode and Zieg classification of pelvic fractures shown on an anteroposterior radiograph of the pelvis.*

of age and early puberty. Understanding development and fusion of the apophyses is helpful for avoiding false positive diagnoses, especially in the setting of trauma (**Fig. 2**).

Double pubic ossification center: It represents a rare variant in infants, seen as a vertical cleft through the middle portion of the superior pubic ramus or as two or more ossification centers, either unilaterally or bilaterally. This finding should disappear during the 1st year of life. The regular and sclerotic margin of the cleft without periosteal reaction and its orientation allow differentiation from fracture, especially in the setting of non-accidental trauma [13].

4. Acute injuries

Paediatric pelvis injuries differ from adult trauma; consequently, numerous peculiarities should be considered. Due to increased elasticity of joints and bony structures together with the cartilaginous abundance, higher energy trauma is required to cause a fracture [14]. Increased joint laxity allows for significant displacement of bones; this biomechanical property has a protective role in paediatric pelvic injury, allowing for "single-site" rather than the traditional "double-break" concept in the pelvic ring. Avulsion apophyseal fractures occur more often in children, especially during growth acceleration, due to cartilaginous frailty which makes the growth plate the weaker link within the muscle-tendon-bone complex [15]. Fractures involving the physeal cartilage can result in late growth arrest and subsequent developmental deformities [16]. Finally, unlike in the mature skeleton, paediatric pelvic fractures are uncommonly associated with significant bleeding, due to increased vasoconstriction and firmer periosteal adherence, which may restrict local bleeding [17].

4.1. Fractures of the pelvis and acetabulum

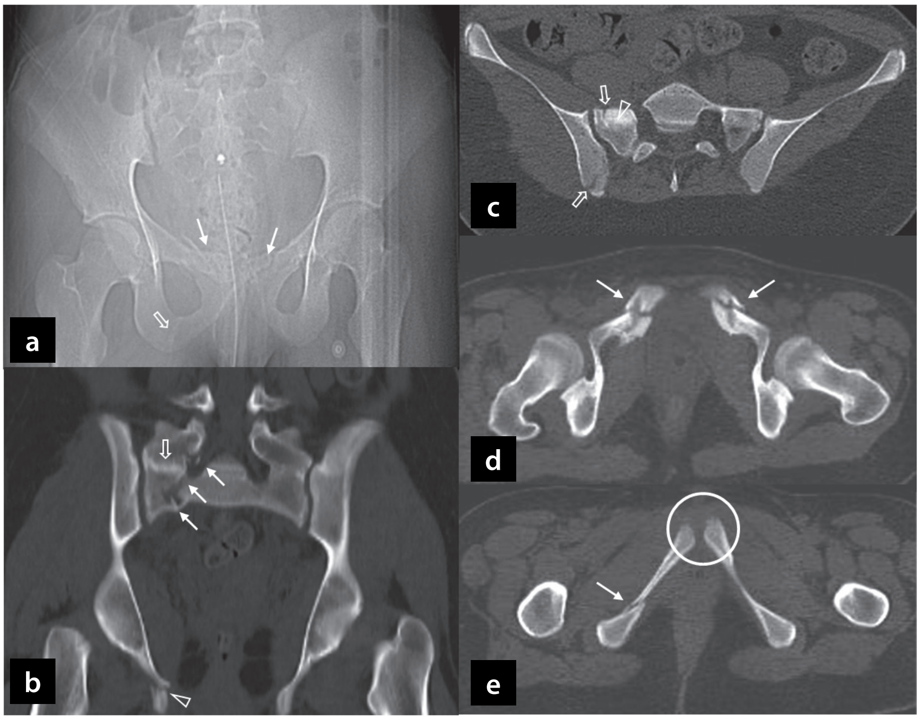

Fig. 5. *CT scan of a 15-year old female passenger in a car accident and a complex stable type A1 injury of the right iliac wing and partially unstable type B injury according to the Tile classification. Scout* ***(a)*** *shows bilateral fractures of the superior pubic rami (arrows) as well as an ischial tuberosity fracture (open arrow). Coronal reconstruction* ***(b)*** *shows additional longitudinal sacral fracture involving the intervertebral foramina (arrows), a sclerotic horizontal area consistent with a compressive injury (open arrow) and a stable ischial fracture (arrowhead). Axial 2 mm scan* ***(c)*** *confirms the asymmetric sclerotic appearance of the sacrum (arrowhead) and depicts iliac and sacral fracture lines (open arrows). Axial 10 mm reconstruction* ***(d)*** *shows the extent of superior pubic rami fractures (arrows). Axial 10 mm reconstruction* ***(e)*** *depicts the right ischial fracture (arrow) and asymmetry in the orientation of the pubic bones around the symphysis pubis (circle).*

Pelvic fractures in children are rare, with an estimated incidence between 0.5% and 7.0% of all blunt paediatric traumas [1, 2, 6]. However, mortality is significant, with a reported average of 6.4%, ranging from 1.4% to 25%, which is mainly attributed to the extent of associated injuries rather than the fracture itself [2, 18, 19]. Up to 95% of pelvic fractures result from high-energy motor vehicle accidents with a pedestrian struck by a motor vehicle representing the most common mechanism [18, 20]. Less common aetiologies include sporting activities which account for 4-11% of all pelvic fractures [19] and child abuse [21]. Acetabular fractures in children are rare and constitute only 1% to 15% of pelvic fractures, with increasing incidence following complete closure of the triradiate cartilage. They are rarely isolated and typically are associated with pelvic, long bone fractures and hip dislocations [22]. Acetabular fractures follow high-energy trauma and do not constitute life-threatening injuries by themselves; however clinical outcome may be disappointing due to articular cartilage injury [23].

Multisystem injuries accompanying pelvic fractures may prove fatal or lead to late sequelae with a reported incidence between 58% and 87% [6, 18, 20]. Brain injuries represent the leading cause of death and long-term disability in children with pelvic fractures, with a reported incidence of up to 57%, while lethal abdominal injuries rank second [18, 22, 24]. Although children with pelvic fractures may require blood transfusions, haemorrhage uncommonly represents the primary cause of death [25]. Incidence of concomitant solid organ injury varies between 14-21%. Vaginal and rectal lacerations are the most prevalent genitourinary injuries, especially in patients with open fractures [26]. Children with gross haematuria should undergo urologic assessment and further imaging [27].

Several classification systems aimed to describe the stability of pelvic fractures and to predict morbidity and mortality [6]. Torode and Zieg [24] divide fractures into stable and unstable by categorising them into four types,

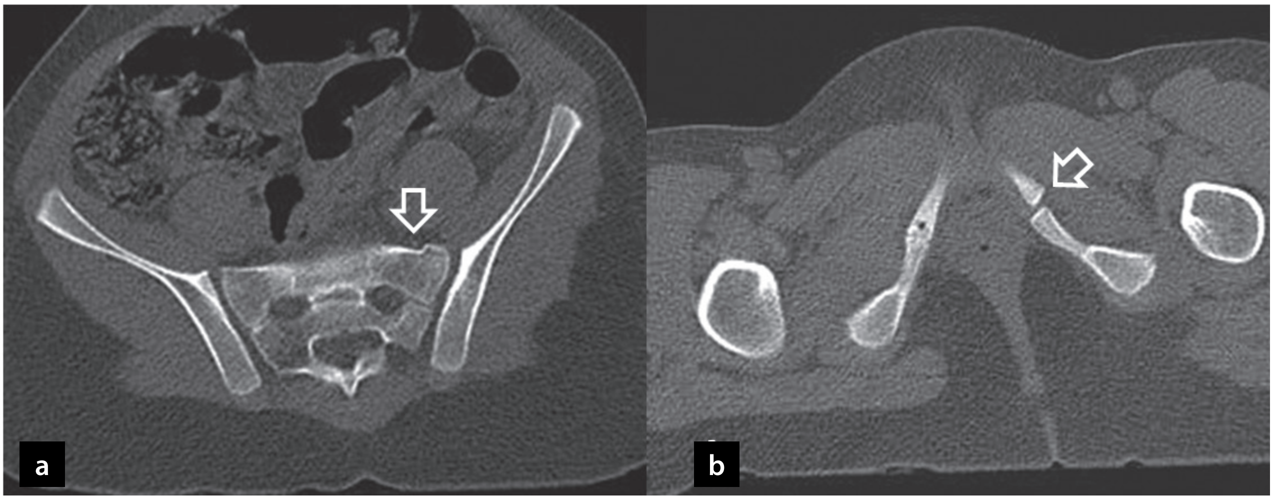

***Fig. 6.** CT scan of a 4-year old pedestrian struck by a car. Pelvic injuries were appreciated following CT. **(a)** Crush injury of the sacrum seen as an undisplaced buckle deformity at the anterior aspect of the sacrum (arrow). **(b)** Diastasis of ischiopubic synchondrosis with mild displacement (arrow).*

accordingly: Type I, avulsion fractures of bony prominences; Type II, iliac crest fracture or separation; Type III, simple fractures of the pelvic ring without instability and Type IV, complex fractures of the pelvic ring with instability (**Fig. 4**). The Tile system combines mechanism of injury with pelvic ring stability and categorises fractures into stable (type A), rotationally unstable (type B) and vertically unstable (type C). Unstable ring disruptions comprise: a. "Straddle" fractures with bilateral inferior and superior pubic rami fractures, b. fractures involving the anterior pubic rami or pubic symphysis and the posterior element, like sacral ala and c. fractures that create an unstable segment between the anterior ring of the pelvis and the acetabulum (**Fig. 5**).

The most useful classification of acetabular fractures is proposed by Bucholz [28] and evaluates the injury in relation to the open triradiate cartilage. Analogue to the Salter-Harris-classification, this classification defines two basic patterns: Type I, shearing type (Salter-Harris Type I or II) and Type II, crushing or impaction type (Salter-Harris Type V). When acetabular injury is suspected, it is important to know the status of the triradiate cartilage with computed tomography (CT) and/or magnetic resonance imaging (MRI). However, except in the very young, it rarely requires surgery [6].

Complications include residual deformity due to malunion or non-union, leg length discrepancies, heterotopic ossification, lumbar scoliosis, incompetency of the pelvic floor, post-traumatic acetabular dysplasia, femoral head necrosis and arthrosis [6, 19]. Age is a significant risk factor in the development of post-traumatic acetabular dysplasia with children younger than 10 years being at greatest risk [28]. The child suffering pelvic trauma should be clinically assessed for life-threatening conditions and stabilised before undergoing any type of imaging.

An anteroposterior radiograph usually suffices for evaluation of pelvic ring stability [29]. In unstable pelvic injury additional inlet and outlet views allow full radiographic evaluation. The inlet view, acquired by angulating the x-ray beam in caudal direction by 60°, is superb for posterior displacement evaluation. The outlet view, obtained by angulating the x-ray beam in cephalad direction by 45°, better evaluates superior displacement or vertical shifting of the anterior pelvis. Additional internal and external rotation views at 45° (Judet views) allow optimal evaluation of the acetabulum. Sacral fractures are difficult to detect on plain radiographs, with the majority of them occurring transversely at the weakest part of the sacral body, the sacral foramen. In these cases, a 35° caudal pelvic view may be helpful. CT with multiplanar reconstructions has mostly replaced additional radiographs for assessment of pelvic fractures [30]. Imaging findings vary significantly according to the type of injury. The presence of a triangular medial metaphyseal fragment (Thurston-Holland sign) has been described in Salter-Harris Type II injuries of the acetabulum, while

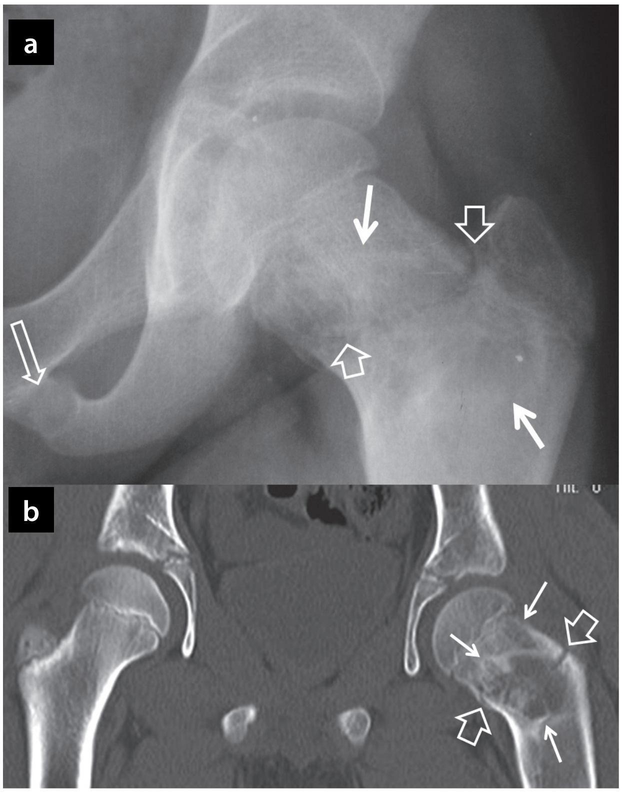

Fig. 7. *Twelve-year-old male footballer with a painful hip following kicking. Fibrous dysplasia in the left proximal hip was not known. Anteroposterior radiograph (a) shows the large, mixed density, lesion (arrows) and a fracture line (open arrows). Unossified left ischiopubic synchondrosis is also shown (long open arrow). Coronal CT reconstruction image (b) shows the fibrous dysplasia lesion to better advantage (arrows) as well as the fracture lines (open arrows).*

narrowing of the triradiate space suggests a crushing type of acetabular injury.

CT is the modality of choice and indicated when the diagnosis on plain radiographs is controversial or pre-operatively (**Fig. 6**) [6, 29]. Adding CT to the diagnostic investigation of paediatric pelvic fractures may change injury classification and management in 15% and 3% of patients, respectively [31]. Furthermore, CT either alone or combined with retrograde cystourethrography, is recommended for children with concomitant findings from abdominal/pelvic examination and complex fracture patterns to exclude visceral, genitourinary and vascular injuries [27, 29]. MRI is recommended for children with unstable pelvic fractures with posterior displacement due to their rare association with lumbosacral plexus or sciatic nerve injury [32]. MRI has the advantages of absence of ionising radiation, better characterisation of soft tissue lesions and detailed evaluation of cartilaginous lesions [33].

4.2. Hip fractures and dislocations

Hip fractures account for <1% of all paediatric fractures and result from high-energy trauma, including contact sports in children >10 years [34-36]; however, in about 10% of patients even minor trauma can result in fracture due to the presence of pre-existing conditions, including unicameral bone cysts and fibrous dysplasia (**Fig. 7**) [35]. Hip fractures are categorised into four types, as proposed by Delbet [35]: type I, transepiphyseal, type II, transcervical; type III, cervicotrochanteric and type IV, intertrochanteric. Associated major injuries, mostly abdominal and pelvic, are also common and present in 30%. Hip dislocations, usually posterior, pelvic and femoral fractures are the most common associated skeletal injuries. Due to the vascular and osseous anatomy of the immature proximal femur, paediatric hip fractures and dislocations should be considered true surgical emergencies in order to avoid complications and long term disability. Femoral head avascular necrosis (AVN) is the most debilitating associated complication, with an incidence depending on pattern of fracture/dislocation, age, amount of displacement and time to surgery/reduction [37]. Physeal arrest, which is usually associated with transepiphyseal type of fracture and AVN, occurs mostly in older children and may result in limb-length discrepancy and secondary deformity [38]. Chondrolysis refers to extensive loss of articular cartilage with resultant joint space narrowing [39]. It is a rare and debilitating disorder which is associated with trauma (**Fig. 8**). Standard anteroposterior, lateral and cross-table radiographs should be included in the primary imaging evaluation of hip fractures. Non-displaced fractures may be radiographically occult; thus, depending on the level of clinical suspicion, CT or MRI may be needed to define the pattern of injury [35]. The Shenton's line, which is a curved line drawn on the anteroposterior pelvic projection extending from the lower femoral neck and following along the top of the obturator foramen, should be evaluated for interruptions, indicative of fracture or developmental hip dysplasia [40]. An acute transphyseal fracture may occasionally resemble a slipped capital femoral epiphysis. These two entities could be differentiated based on the high-energy mechanism required to cause a fracture and documentation of a normal physis before injury. Comparison with the contralateral hip may help diagnose an acute

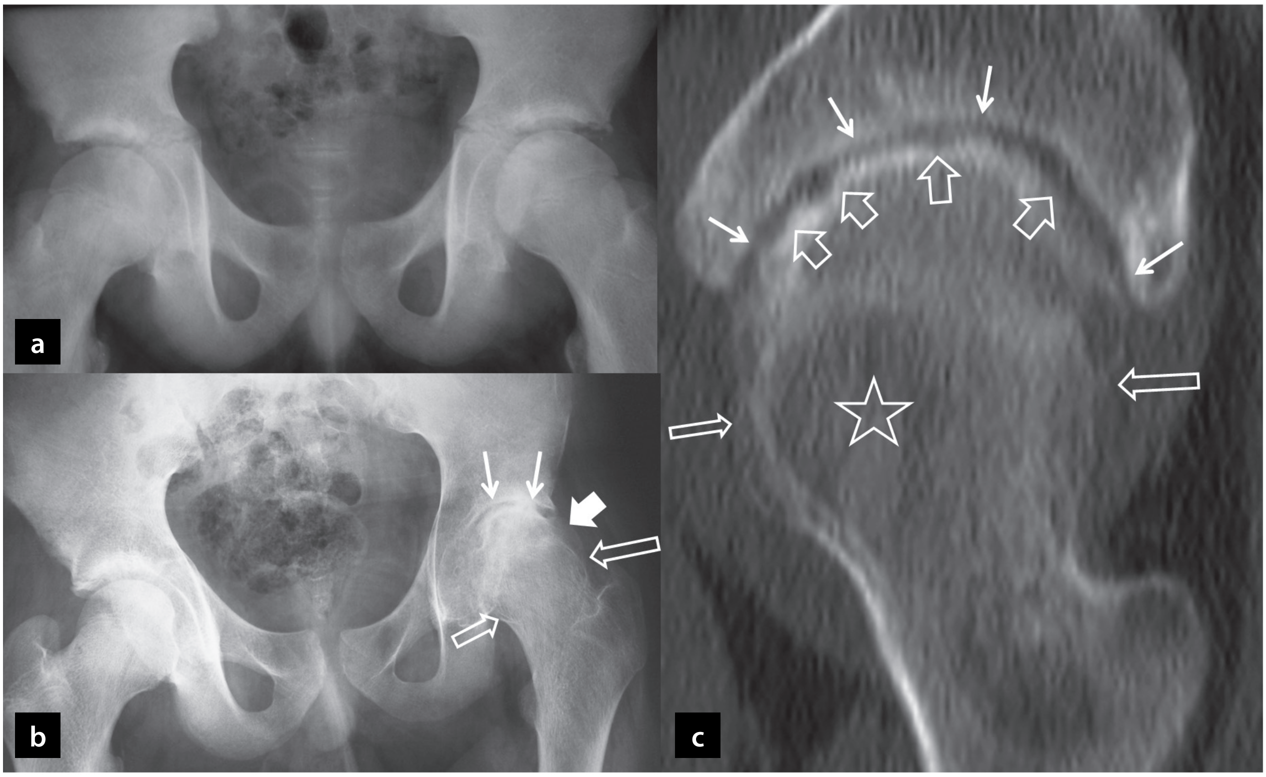

Fig. 8. *A 16-year-old male with chondrolysis following posterior dislocation of the left hip after a bicycle accident. Anteroposterior view **(a)** immediately following reduction shows symmetrical joint space width at hip joints. One year later, anteroposterior view **(b)** and oblique axial CT reconstruction **(c)** show joint space narrowing in the left hip (arrows), irregular articular surface (open arrows), osteopaenia (asterisk), lateral femoral buttressing (solid arrow) and increased femoral head/neck width (thin open arrows).*

slip, especially when the contralateral physis is widened.

The radiographic protocol in patients with hip dislocations, apart from the standard evaluation, should also include Judet views. In young children with incomplete ossification of the head, pain should increase the level of suspicion for a completely dislocated head which may be obscured behind the ileum [41]. CT or MRI are indicated for the evaluation of joint incongruency and post-reduction instability, especially in elite athletes [36]. MRI following successful closed reduction of a hip dislocation assesses associated osteochondral, labral or soft tissue injuries, while CT may excellently depict intra-articular loose bodies.

Plain radiographs have a low specificity in detecting early changes of AVN which become radiographically apparent between 2-12 months post-injury [36]. MRI has currently an invaluable role in the early detection of AVN. In patients with suspected post-traumatic AVN, performance of MRI at 4-6 weeks following trauma is recommended. Patients with normal bone marrow signal intensity belong to the low risk group for AVN development, while those showing signal abnormalities should undergo an additional MRI study in order to confirm or exclude AVN [42].

4.3. Apophyseal avulsion fractures

Apophyseal avulsion fractures occur with increasing frequency, accounting for 10% to 24% of all athletic injuries in children [43]. Boys are affected more often than girls. Since the weakest biomechanical point of the muscle-tendon-bone unit in the immature pelvis is the growth plate, excessive force on this chain tends to result in apophyseal avulsion fractures. Acute avulsions occur following forceful traction of large muscles which have their attachments on the pelvic apophyses (**Fig. 2**). The implicated mechanism is either active muscular contraction during sports like soccer, running, sprinting and jumping or sudden traction following excessive muscular stretching occurring in gymnastics or ballet dancing [43, 44]. Avulsion fractures of the ischial tuberosity account for more than 50% of these injuries followed by avulsions of anterior inferior iliac spine,

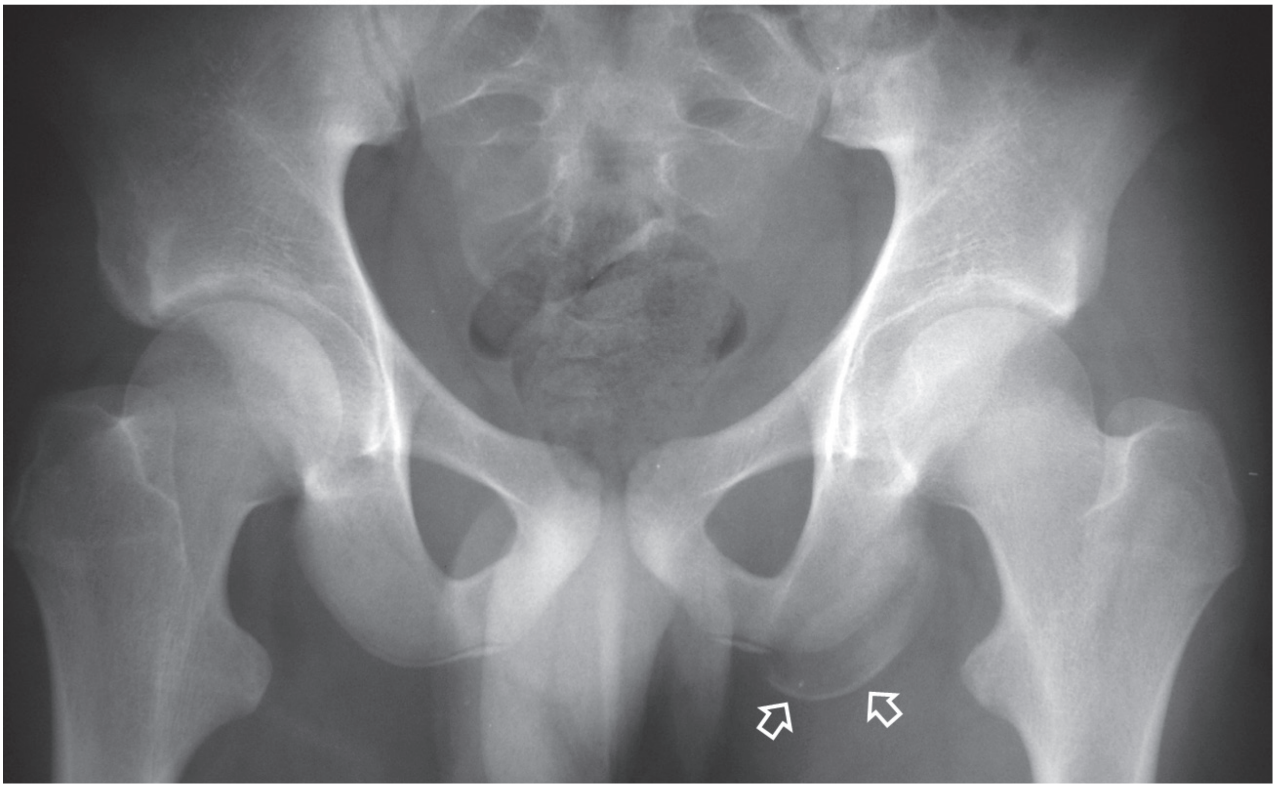

Fig. 9. Radiographic evaluation of a 16-year old tennis player with an episode of acute pain and a popping sound during training. There is a typical avulsion of a fractured and displaced ischial tuberosity apophysis (arrows).

whereas avulsions of the lesser trochanter and iliac crest are rare [45, 46].

In typical cases the diagnosis is straightforward: a popping sound and acute onset of pain and disability following known muscular maneuver(s) coupled with confirmatory radiographic findings. On the other hand, when there is no recall of a specific traumatic event, radiographic findings may be challenging because post-traumatic changes can simulate osteomyelitis or even malignancy [44].

Typically, in the acute phase, non-displaced avulsions of the apophyses appear as curved, sharply marginated pieces of bone adjacent to the corresponding apophysis' origin (**Fig. 9**) [44]. In cases of displaced fractures, the distance between the displaced fragment and mother bone is important because displacement of >2 cm may result in a fibrous union and disability [44]. When radiographs place the diagnosis in doubt, bony details are better delineated with CT, ultrasonography (US) and MRI [44]. Knowledge of the anatomy of musculo-tendinous insertions, comparative US scanning and appropriate history contribute to the correct ultrasonographic diagnosis [47] (**Fig. 10**). MRI should be reserved for doubtful cases and offers direct evaluation of the tendon attached to the avulsed apophysis, which may have a lax configuration due to retraction. Variable degree of oedema in regional soft tissues and involved bones is usually depicted on fluid sensitive images (**Fig. 10**). In avulsion fractures involving the symphysis pubis or pubic ramus, discrete bony fragments are rarely seen, in contrast to injuries at other sites. MRI may clarify the specific muscle involved and characterise this type of injury [48].

4.4. Slipped capital femoral epiphysis

Slipped capital femoral epiphysis (SCFE) is a Salter-Harris type I fracture through the proximal femoral physis, affecting mainly males, with a peak incidence between 10 and 17 years for boys and 8 to 15 years for girls [49, 50]. Risk factors include increased body mass index, malnutrition, endocrine abnormalities, acute or repetitive injury with increased shear forces parallel to epiphysis and developmental hip dysplasia, especially if slippage occurs prior to adolescence [50]. The exact aetiology of SCFE remains unclear. According to a proposed theory, there is widening of the physeal plate during growth, which is particularly pronounced during growth spurt. Additionally, the orientation

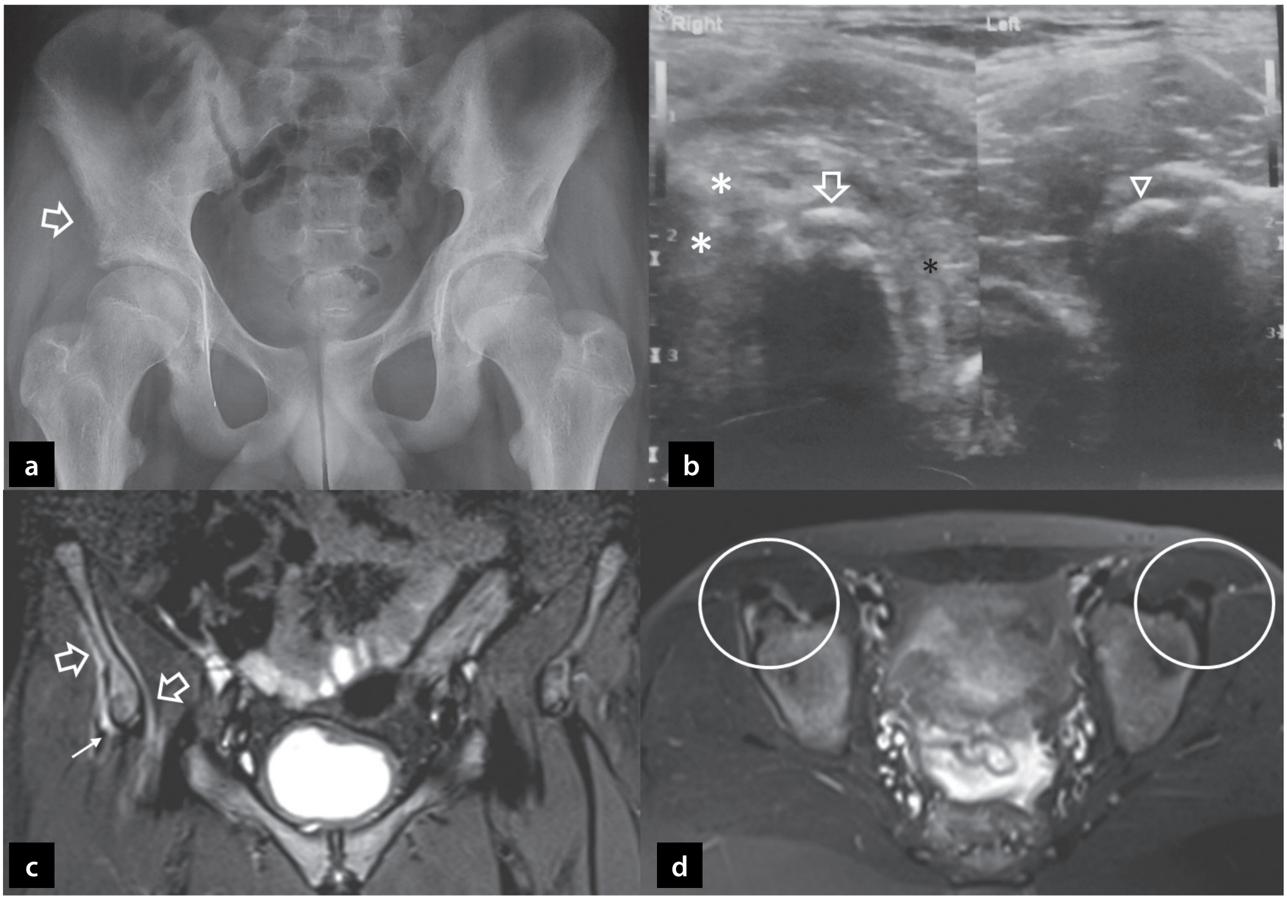

Fig. 10. Radiographic evaluation of a 15-year old soccer player with pain over the right pelvis, 2 days following an episode of painful stretching. Anteroposterior view at presentation ***(a)*** *shows an ill-defined chip of bone off the area of the AIIS (arrow). US evaluation* ***(b)*** *of the same patient shows increased echogenicity (*) around the right AIIS (arrow) compared to the left AIIS (arrowhead). Coronal fat suppressed T2W MR image at presentation* ***(c)*** *shows soft tissue hyperintensity around the iliac bone (arrows) and especially by the site of rectus femoris tendinous insertion (long arrow). Axial fat suppressed T2W MR image* ***(d)*** *confirms asymmetry at the areas of AIIS (within circles). Patient was treated with bed rest and completely recovered.*

of the physis changes from horizontal to oblique, which results in increased vertically oriented shear forces, increased risk of fracture and resultant slippage [51].

Anteroposterior and "frog-leg" lateral radiographs should include both hips for comparative assessment and because of the high incidence of bilateral involvement [52]. Early radiographic findings on the anteroposterior projection include widening and irregularity of the growth plate and osteopaenia of the femoral head/neck due to demineralisation. This is followed by the acute slip which may be more prevalent on the "frog-leg" lateral view when subtle [52]. As the slip progresses, the femoral epiphysis moves posteriorly and may appear smaller due to projectional factors, while there may be further widening of the physis. In more advanced cases there is displacement of the femoral neck with regard to head. In chronic stages, the physis becomes sclerotic and the metaphysis widens [50]. Klein's line can be drawn on the anteroposterior view along the superior aspect of the femoral neck, which should not intersect the femoral head in SCFE (**Fig. 11**) [53]. The metaphyseal "blanch" sign on anteroposterior views describes increased density of the proximal femoral metaphysis which is attributed to superposition of the femoral neck.

MRI can detect and stage SCFE (**Fig. 12**). Multiplanar imaging is important due to the spacial complexity of this entity. Both hips should be included in the study because of the high prevalence of bilateral involvement. The earliest MRI evidence of SCFE is physeal widening. Increased bone

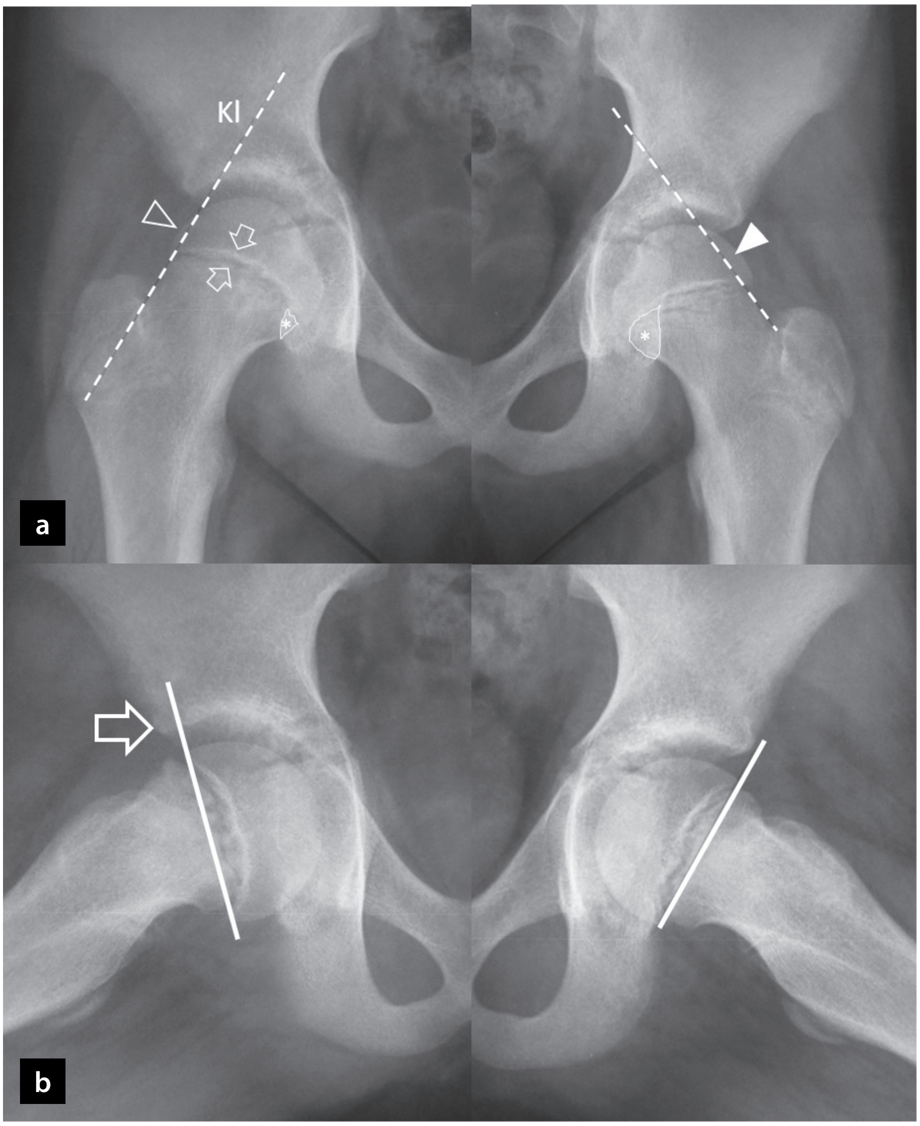

Fig. 11. Radiographic evaluation of a 10-year old female with right hip pain for 2 weeks. Anteroposterior views of both hips ***(a)*** *show that Klein's line (dashed Kl) on the right, coursing tangentially the lateral femoral metaphysis, barely intersects the femoral head (arrowhead), as opposed to the left (white arrowhead). There is also widening of the right physis (open arrows) and a smaller percentage of proximal femoral metaphysis overlying the ischial bone (*) on the right, compared to the left. Frog-lateral view of both hips* ***(b)*** *confirms physeal widening on the right and an anteriorly displaced metaphysis in relation to the femoral head. The line crossing the physis on the right lies medial to acetabural edge (arrow) as opposed to the left.*

marrow signal intensity along the physis on fluid sensitive sequences indicates stress and oedema; however this represents a non-specific finding [54].

Although MRI appears to be the modality of choice regarding the depiction of early slips, US comparing hip joints can be used as an alternative method for initial diagnosis and staging of SCFE. Key findings include joint effusion, widening of the growth plate and posterior displacement of the epiphysis relative to the metaphysis.

4.5. Muscle injuries

Soft tissue injuries around the hip and pelvis are common among athletes and can result in significant abstain from training. Muscle injuries are divided into contusions and strains. Contusions are caused by direct impaction to a muscle and are seen in contact and collision sports like football and hockey, with the quadriceps muscle being most

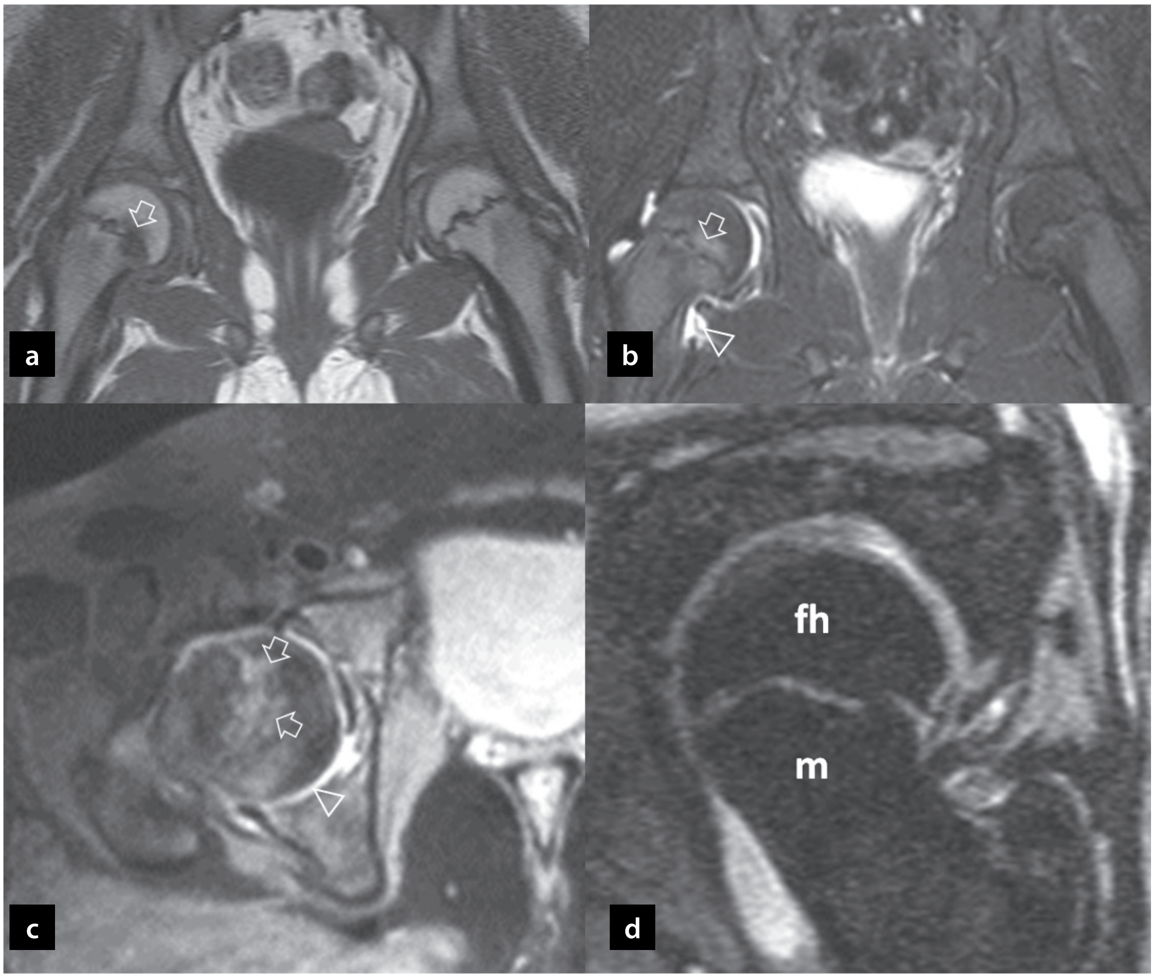

***Fig. 12.** MRI of the same patient as in Fig. 11. Coronal T1W MR image **(a)** showing low signal intensity by the growth plate (arrow). Coronal **(b)** and axial **(c)** fat suppressed T2W MR images showing bone marrow hyperintensity (arrows) by the widened physis and joint effusion (arrowheads). Oblique sagittal T2* MR image **(d)**, accurately depicts the degree of anterior displacement of the metaphysis (m) in relation to the femoral head (fh).*

commonly affected [55]. Strains occur from indirect injuries following acute trauma or overuse, usually due to eccentric contraction. These represent the most common injuries around the hip and pelvis in adolescent athletes [5]. Frequently affected muscles include hamstrings, adductor longus, rectus abdominis, iliopsoas and rectus femoris [55].

Imaging characteristics depend on clinical grades of muscular strains. Grade I lesions present with mild or moderate pain without any functional deficit. MRI reveals focal or general intra-substance hyperintensity in a "feathery" pattern on fluid sensitive sequences, without discontinuity of muscle fibers (**Fig. 13**) [55]. On US, the muscle may appear normal or show areas of increased echogenicity with/out perifascial fluid [56]. Grade II lesions are characterised by partial functional deficit. MRI shows areas of hyperintensity on fluid sensitive sequences together with partial intra-substance tearing. Haematomas typically form at the musculo-tendinous junction during that stage, exhibiting varying signal characteristics depending on chronicity [5]. On US, there is discontinuity of muscle fibers with presence of intramuscular fluid collection usually with a surrounding hyperechoic halo. Hypervascularity around the disrupted muscle fibers may increase lesion conspicuity on colour Doppler. Dynamic scanning during contraction accurately defines the size of the lesion [57]. Grade III lesions are relative uncommon in the growing skeleton, with complete disruption of the musculo-tendinous junction and significant loss of function. Both US and MRI depict complete discontinuity of muscle fibers and associated haematoma. The "clapper in bell" sign is a US sign describing the retract-

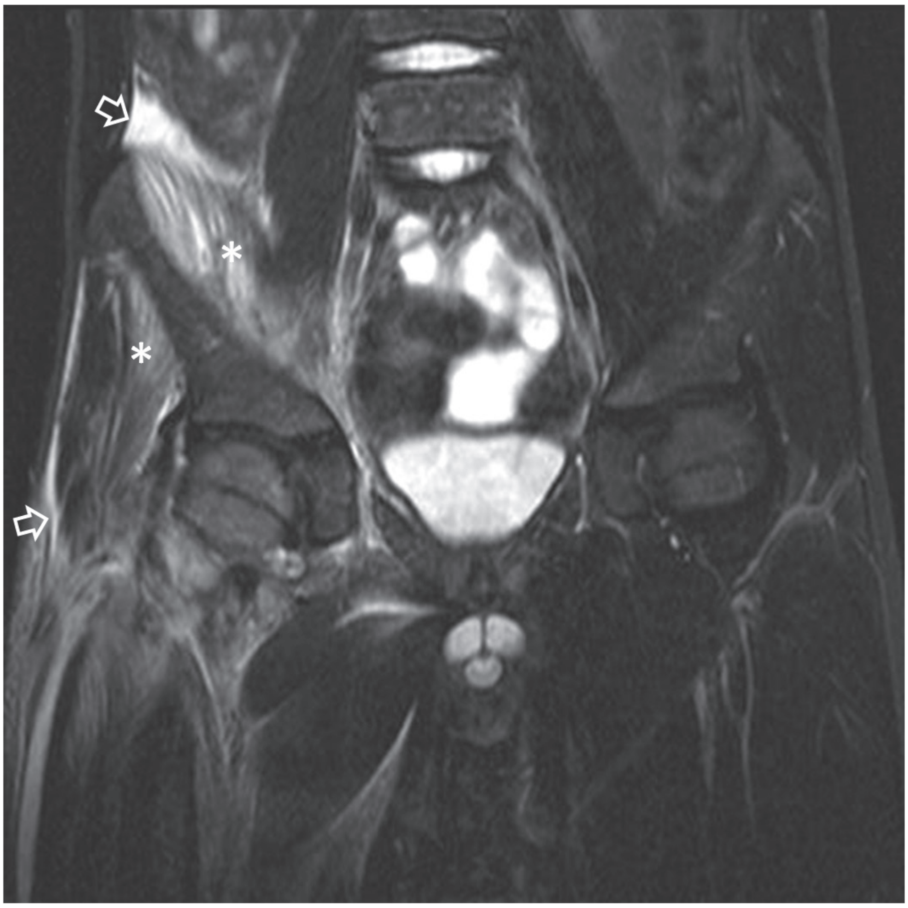

Fig. 13. Coronal STIR MR image of a 10-year old male footballer with extensive Grade I muscle injury. Feathery pattern at the iliac and medial gluteus muscles (*) appreciated as alternating hyperintense oedema among hypointense lines representing intact muscle fibers. Also note hyperintense fluid at fasciae (arrows).

ed echogenic muscle fragments surrounded by hypoechoic haematoma [56].

Long-term complications depend on severity of the initial injury and proper rehabilitation. Fibrous scars may form after recurrent or severe muscle strain [56]. Herniation of muscle fibers through a weakened aponeurosis or fascia following blunt or penetrating trauma may be sonographically confirmed during muscle contraction. US shows the hernia clearly consisting of normal muscle fibers [56]. Myositis ossificans may mimic aggressive disorders on plain radiographs. It becomes apparent within 2-6 weeks and reaches typical radiographic appearances of a well-circumscribed calcification with a lucent center, by two months. Thereafter, regression should begin [58]. CT is the examination of choice and depicts a cleft separating the lesion from the cortex of the adjacent bone [58]. On US it appears as a hypoechoic mass with sheets of echogenic material. Later, areas of coarse calcification parallel to the adjacent diaphysis may appear. MRI during early stages can be misleading because peripheral calcification is not well formed, lesions exhibit abnormal signal intensity (isointense to muscle on T1-W sequences, peripheral hyperintensity due to oedema and central heterogeneity due to cellularity on fluid sensitive sequences) and contrast enhancement. On late stages, there is typically a peripheral hypointense rim on all pulse sequences, representing mineralisation [58].

5. Chronic injuries

Chronic pelvic injuries result from repetitive micro-trauma following high level physical activity and are mostly self-limiting conditions. However, atypical clinical or radiological appearances represent a diagnostic challenge.

5.1. Chronic avulsion fractures/apophysitis

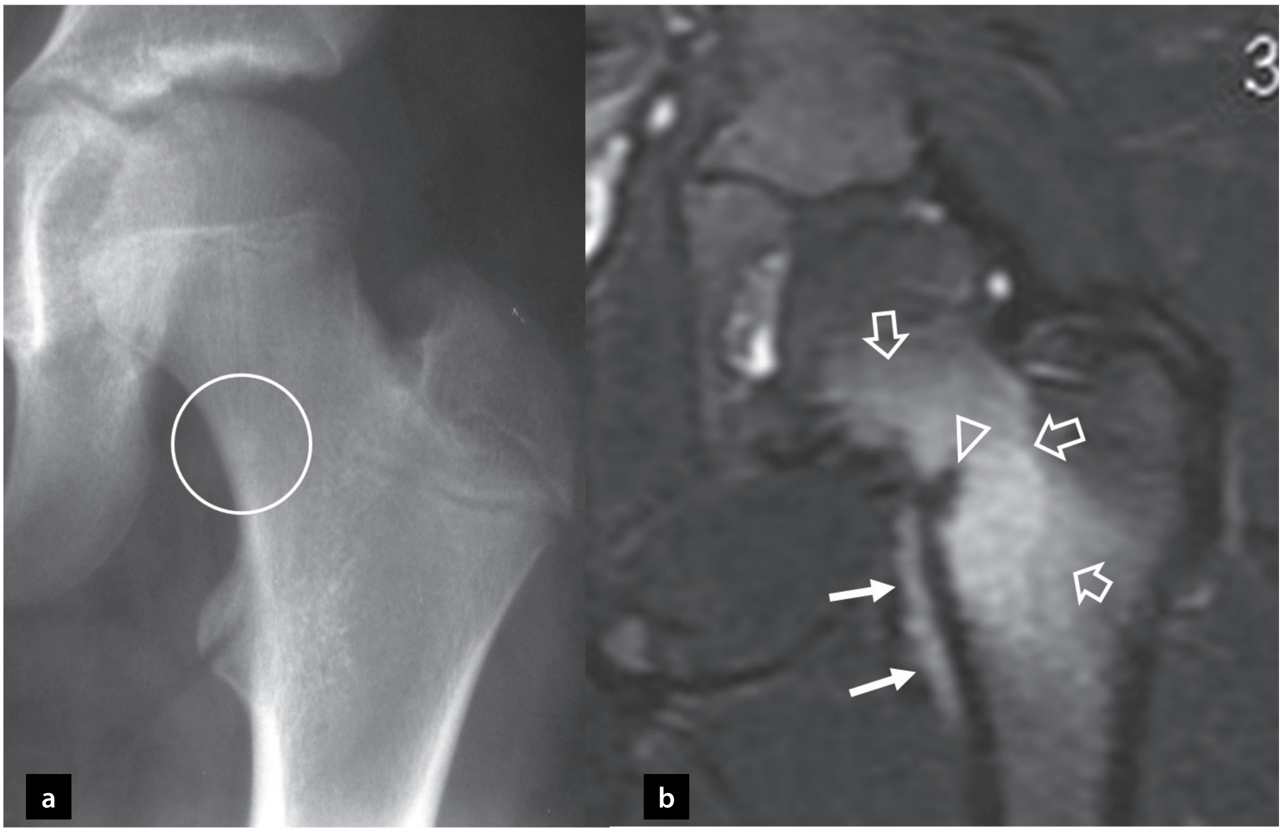

*Fig. 14. A 11-year old ballet dancer with a stress fracture. Anteroposterior radiograph **(a)** shows an ill-defined band of sclerosis at the medial aspect of the left femoral neck (within circle) coursing perpendicular to supporting trabeculae. Coronal STIR MR image **(b)** shows extensive bone oedema (open arrows) surrounding the hypointense band representing the fracture line (arrowhead). Associated hyperintense soft tissue oedema is also shown (long arrows).*

Chronic apophyseal avulsions or traumatic apophysitis constitute overuse injuries following traction due to repetitive contraction of attached muscles, leading to chronic apophyseal inflammation. Apophysitis is more prevalent in children participating in sports known to induce stress on specific apophyses [59]. Sites of apophysitis are identical to the sites where acute avulsions occur.

At radiography, chronic or healing avulsions may appear aggressive, as areas of lysis/destruction, fragmentation of the apophyseal margin and widening of the involved physis. In the absence of a clear history of trauma, appearances may mimic osteomyelitis or Ewing sarcoma [60]. Chronic avulsions are frequently associated with exuberant callus formation which may impinge on nerves and cause sciatica. In such cases, CT is useful. MRI represents the modality of choice and is performed following conservative treatment failure. Typical imaging findings include enlargement of the apophysis, subentheseal bone marrow oedema and epiphyseal plate separation, depicted as a widened hyperintense line on fluid-sensitive sequences. Variable peri-apophyseal soft tissue and muscular oedema with enhancement may occur [59].

5.2. Stress fractures and stress reactions

The increased incidence of stress injuries has been attributed to the increased number of children participating in competitive sports [4]. Stress fractures result from repetitive non-violent axial loading on the skeleton without sufficient time for recovery and are distinguished into fatigue fractures, resulting from excessive forces applied on normal bone and insufficiency fractures resulting from normal or minimally increased forces on abnormal bone [61]. Stress reaction is the initial response of bone to stress, which may progress to stress fractures if abnormal loading persists. Skeletally immature individuals are particularly prone to stress injury. Hormonal changes, weaker osteochondral junctions, thinner cortices and decreased mineralisation may explain this predisposition [62]. The female athlete triad

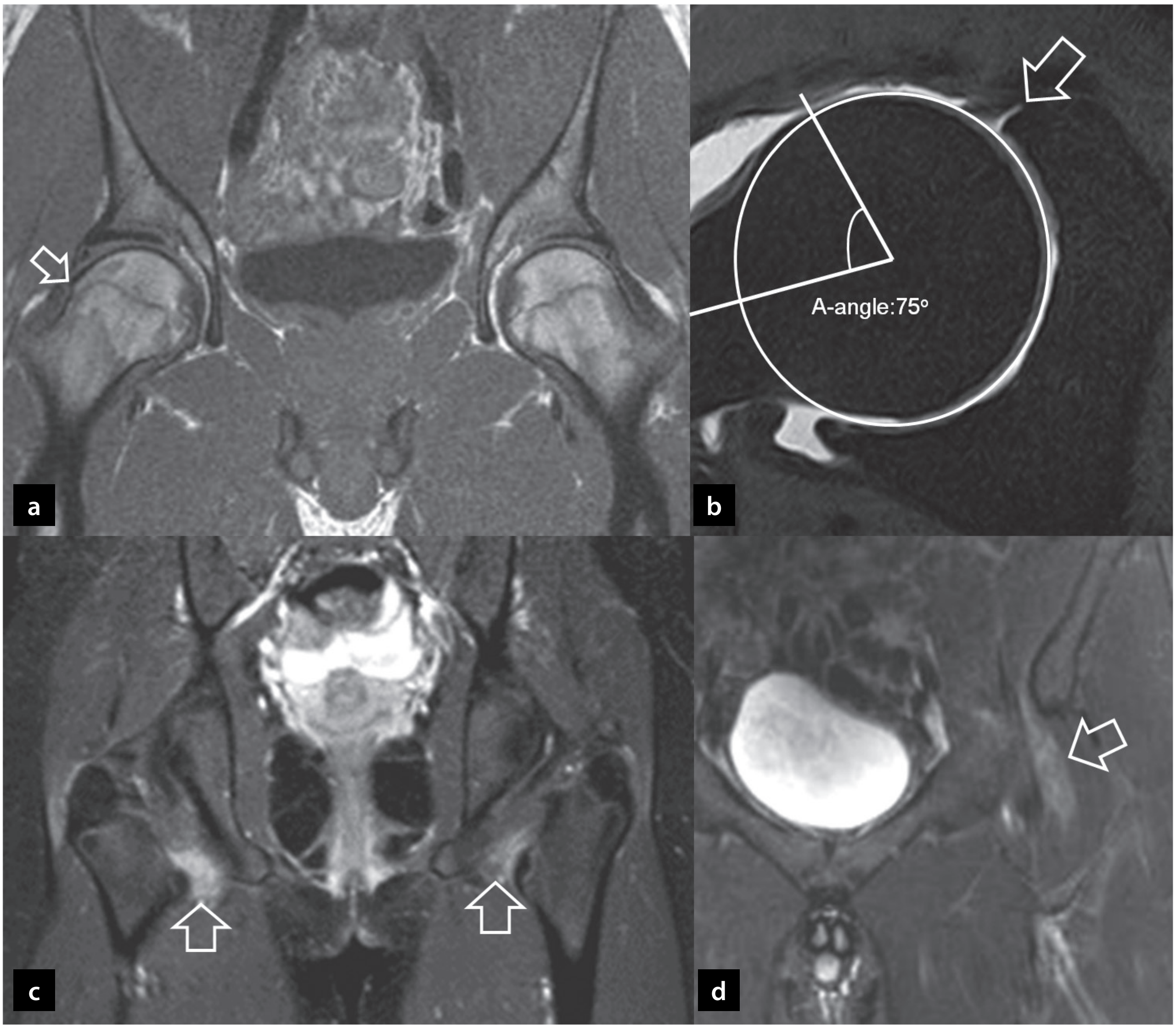

*Fig. 15. A 16-year-old male football player with a clinical diagnosis of "Cam" type femoroacetabular impingement **(a, b)**. Coronal T1W MR image **(a)** shows the osseous bump, also called "pistol-grip" deformity (arrow). The oblique axial fat suppressed MR arthrographic image **(b)** shows a labral tear (arrow) and an abnormal A-angle. A 13-year-old ballet dancer with a clinical diagnosis of ischiofemoral impingement on the right **(c)**. Coronal STIR MR image **(c)** shows increased signal in both quadratus femoris muscles (arrows), more extensive on the right. A 16-year-old male outdoor elite rower with snapping left hip and pain **(d)**. Coronal STIR MR image **(d)** shows increased signal intensity along the iliopsoas tendon (arrow).*

describes the relationship between caloric imbalance, hormonal dysregulation and impaired bone mass, predisposing to injury with fatigue and insufficiency components [63]. Sacral and pubic bone stress fractures are usually seen in young runners and less frequently in athletes who participate in volleyball, ballet or gymnastics [62]. Femoral stress fractures are more frequently seen in runners or soccer players following skeletal maturity [62]. Abnormal weight bearing due to coxa vara of the proximal femur is a predisposing factor [64].

Conventional radiographs detect only 15% of stress fractures in the acute setting as sclerotic lines perpendicular to supporting trabeculation with/out subtle periosteal reaction [61]. Radionuclide scans have high sensitivity but low specificity. Stress fractures on scintigraphy may be mistaken for bone tumours or osteomyelitis [65]. MRI depicts stress reactions as marrow oedema which enhances homogeneously following contrast administration [66]. Stress fractures are depicted as well-defined low signal intensity linear lesions extending to the cortex. Identification of sub-periosteal fluid is a helpful associated finding in subtle fractures [66] (**Fig. 14**).

5.3. Femoroacetabular impingement

Femoroacetabular impingement (FAI) has been recognised as a clinical syndrome of anterior hip pain aggravated with flexion activities, characterised by decreased hip internal rotation, and a positive impingement sign [67]. FAI is associated with premature osteoarthritis due to morphologic deformities at the femoral head-neck junction or acetabulum [67, 68] predisposing to abnormal contact. FAI can also occur at extremes of movement, despite normal bony geometry [69]. It has also been associated with posterior hip instability in adolescents [70].

The two types of FAI, the "Pincer" and "Cam" may coexist in the mixed type [68]. The "Cam" type refers to presence of a bony bump at the femoral head-neck junction causing an insufficient head-neck offset (**Fig. 15a**). While the non-spherical portion of the head impinges on the acetabulum, shear stress is applied on the chondrolabral and osteochondral junction, resulting in chondral injury. Proximal hip deformity can be idiopathic or associated with SCFE and Perthe's disease [71-73]. "Pincer" is characterised by overcoverage of the femoral head due to acetabular retroversion or global overcoverage. During hip movement, abutment of the proximal femur against the prominent acetabulum induces labral degeneration, rim ossification and increased overcoverage [68]. Persistent abutment induces "contre-coup" chondral injury of the posteroinferior acetabulum due to repetitive, subtle subluxation [74].

Imaging work-up of FAI should begin with routine plain radiographs [75]. MRI or MR arthrography should be utilised for assessing cartilage and labrum. Pathologic values for radiographic measures of FAI are not clearly defined in the growing skeleton; however they do differ significantly compared to adults. Femoral head asphericity is quantified by measuring the Alpha angle. This is defined as the angle between the femoral neck axis and a line connecting the center of the femoral head with the point where asphericity begins. Values >55° are considered abnormal [76]. There are numerous quantitative methods for assessing acetabular coverage. The lateral center edge angle is formed by a vertical line and a line connecting the femoral head center with the lateral acetabular edge. Values >40° indicate acetabular overcoverage whereas angles <20° suggest developmental hip dysplasia [77]. Acetabular retroversion is identified on frontal views with the "crossover" sign which is present when the anterior acetabular rim crosses over the posterior rim. A retroverted acetabulum is identified on axial images when the anterior acetabular rim extends lateral to the posterior rim, on the most cranial image that includes the femoral head [78]. Herniation pits seen as well defined lytic lesions located at the femoral head-neck junction are currently linked to FAI [79].

On MRI, Alpha angle measurement is subject to poor intra-observer reliability and values >55° are considered abnormal [76]. Labral avulsions, mainly at the labral-cartilage interface, appear on MR arthrography as hyperintense clefts extending through the labral base (**Fig. 15b**) [80]. Labral abnormalities in Cam typically involve the anterosuperior whereas in Pincer are located at the anterosuperior and posteroinferior quadrant [76, 80, 81]. It should be pointed out that abnormal hip joint morphology in paediatric patients may not reflect the fully formed pathologic abnormalities seen in adults; thus even subtle changes should be mentioned and followed-up regularly.

5.4. Ischiofemoral impingement

Ischiofemoral impingement syndrome refers to impingement of the quadratus femoris muscle due to narrowing of the ischiofemoral space. Ischiofemoral narrowing can be evaluated by measuring the ischiofemoral space (IFS) and the quadratus femoris space (QFS). The IFS is defined as the minimum distance between the lateral cortex of the ischial tuberosity and medial cortex of the lesser trochanter while QFS represents the smallest distance between the superolateral surface of the hamstring tendons and the posteromedial surface of the iliopsoas tendon or lesser trochanter [82].

The incidence of ischiofemoral impingement syndrome in the paediatric population has not been investigated. Its pathophysiology has been related to developmental, positional and acquired factors. Developmental factors include increased femoral neck-shaft angle, increased ischial and femoral neck angle and wide inter-tuberous diameter [83, 84]. Acquired aetiologies have been associated with non-union inter-trochanteric fractures, lesser trochanter exostosis and chronic hamstrings' avulsion among others [85, 86].

Plain radiographs may be normal or reveal sclerosis and subcortical cysts in the lesser trochanter or ischium [87].

MRI represents the modality of choice and reveals reduction of the IFS and/or QFS with crowding and abnormal signal of muscular fibers. Cut-off values of IFS ≤17 mm and QFS ≤8 mm are indicative criteria in adults [82]. Oedema of quadratus femoris muscle is best seen on fluid-sensitive sequences, whereas muscular fatty infiltration or tear are better seen on T1-W images without fat-suppression [82, 88] (**Fig. 15c**). Clinical correlation is of outmost importance in order to avoid over-diagnosis.

5.5. Snapping hip syndrome

Snapping hip refers to a palpable or auditory snapping during movement of the hip joint [89]. It is more prevalent in dancers, soccer players and runners involved in sports requiring repetitive hip flexion and extreme hip motion [90]. The syndrome is categorised as extra-articular, either external or internal, or intra-articular. External syndrome describes the restricted sliding of a thickened iliotibial band or gluteus maximus muscle/tendon over the greater trochanter, during the return of the hip from flexion to full extension. Internal syndrome refers to impingement of the iliopsoas tendon typically over the iliopectineal eminence [89] and is reproduced when the hip is extended from a flexed, abducted and externally rotated position. Intra-articular causes are related to the presence of loose bodies, labral tears or cartilaginous flaps, synovial folds and osteochondral fragments [91]. Regarding external snapping hip syndrome, MRI may depict trochanteric bursitis and oedema along the involved structures. Since oedema may be present in asymptomatic adult individuals, clinical correlation is required to avoid over-diagnosis [92]. The absence of bursitis on MRI has been related to high negative predictive value for associated pain [93]. US can not only detect soft tissue changes but also confirm the synchronous presence of abrupt movement of the involved tendon and the typical snap, during dynamic maneuvers [94, 95]. In internal snapping MRI may depict indirect signs including iliopsoas bursitis and tendinopathy or oedema along the iliopsoas tendon (**Fig. 15d**). However these findings cannot usually establish a diagnosis and are also seen in asymptomatic individuals. For intra-articular causes, MR arthrography is the modality of choice, with arthroscopy remaining the gold standard. Pain relief following intra-articular injection of anaesthetic during the procedure can be used in order to confirm the intra-articular source of symptoms.

6. Differential diagnosis

Pain around the hip and pelvic in children and adolescents carries a wide differential diagnosis. Even in the setting of preceding trauma or involvement in intense physical activities, radiologists and clinicians should have a high index of suspicion for diseases that may simulate post-traumatic conditions. Alternative diagnoses should include transient synovitis, Legg-Calvé-Perthes disease, infectious and inflammatory processes like septic arthritis, osteomyelitis, juvenile idiopathic arthritis and chronic recurrent multifocal osteomyelitis, as well as tumours like osteoid osteomas, fibrous dysplasia, Langerhans cell histiocytosis, osteosarcoma, Ewing's sarcoma, leukemia and metastases [96-98].

7. Conclusion

Traumatic injuries of the paediatric pelvis and hip may occur in the acute setting or manifest with non-specific pain and disability, mimicking non-traumatic conditions. The weakest biomechanical point of the muscle-tendon-bone unit in the immature paediatric pelvis is the growth plate by the apophyses and femoral capital epiphysis, resulting in age-dependent types of injuries. Radiographs and CT are the imaging modalities of choice for the evaluation of pelvic and hip fractures. MRI in combination with radiographs is essential for the investigation of chronic hip pain in athletes with musculotendinous and non-displaced avulsion injuries. US carries an emerging role in both acute and chronic injuries. R

Conflict of interest

The authors declared no conflicts of interest.

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