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Femoroacetabular Impingement

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Abstract

There is evidence that Femoroacetabular Impingement (FAI) is a major aetiologic factor in end stage Osteoarthritis (OA) of the hip, particularly in the young adult. These patients are usually very active who suffer with persistent or intermittent groin pain. Recent studies have found that the majority of these investigated cases have evidence of mild bone abnormalities. These deformities can occur on either the pelvic or femoral side or a combination of both. They interact to reduce the amount of clearance between the femoral neck and acetabular rim. This results in repetitive early contact between these osseous prominences which if left untreated will eventually progress to OA. This study reviews the clinical presentation, diagnosis and research with regard to FAI. Significant findings include the confirmation that there are gender differences in FAI morphology as well as a strong correlation between the clinical diagnosis of FAI with motion simulations and the soft-tissue damage observed intra-operatively. However, it has been shown that FAI morphology is common within the normal population and presence of this morphology alone does not necessarily mean that subjects will experience motion restriction or joint degeneration. Consequently, the type and intensity of activity a person undertakes as well as presence of more than one radiological indication of FAI contribute to the progression towards OA. Further, the analysis of the activities that a person with FAI undertakes must consider the motion of the pelvis as well as the relative alignment of the femur and pelvis in the neutral posture. These factors along with the bone morphology dictate whether impingement will occur as well as its overall severity. This should be the basis of further development with regard to the motion analysis and simulation of FAI patients to obtain a more accurate diagnosis which the surgeon can respond to have a more effective surgical plan.

Contents

Glossary

APP	Anterior Pelvic Plane, 15
CCD	Caput-Collum-Diaphyseal, 9
CT	Computer Tomographic, 7
DDH	Developmental Dysplasia of the Hip, 1
FAI	Femoroacetabular Impingement, 1
MR	Magnetic Resonance, 7
MRA	Magnetic Resonance Arthography, 7
MRI	Magnetic Resonance Imaging, 7
OA	Osteoarthritis, 1
SCFE	Subclinical Slipped Capital Femoral Epiphysis, 1
THA	Total Hip Arthroplasty, 1

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1 Introduction

Osteoarthritis (OA) of the hip is a degenerative joint disease with diverse aetiologies (Ganz et al., 2003). The underlying causes of OA are complex with many different risk factors that include - age, gender, race, obesity, occupation, ligamentous instability, genetic inheritance and a history of hip disorder in childhood (Goodman et al., 1997; Gosvig et al., 2007). However, 80% of patients treated with Total Hip Arthroplasty (THA) are diagnosed with primary or idiopathic OA which indicates that no aetiological factors can be determined (Ganz et al., 2003; Gosvig et al., 2010). Many secondary cases of OA are a result of deformities developed or acquired as a child. These include Developmental Dysplasia of the Hip (DDH), Legg-Calvé-Perthes disease and Subclinical Slipped Capital Femoral Epiphysis (SCFE)(Goodman et al., 1997; Ganz et al., 2008; Leunig et al., 2009; Philippon et al., 2012). However, a number of studies have suggested that milder deformities are a significant cause of OA later in life (Goodman et al., 1997; Murray, 1965; Stulberg et al., 1975). Therefore, many idiopathic cases of OA can be attributed to these minor developmental deformities which have previously been unrecognised or ignorned (Ganz et al., 2008). The collective name for these minor deformities is Femoroacetabular Impingement (FAI)(Clohisy et al., 2010).

Today, there is more evidence that FAI is a major aetiological factor in end stage OA of the hip, particularly in the young adult (Clohisy et al., 2010; Leunig et al., 2009; Murphy et al., 2004; Neumann et al., 2009). These patients are usually very active who suffer with persistent or intermittent groin pain (Ganz et al., 2003; Wyss et al., 2007). This pain is associated with damage to the hip joint cartilage and labrum which progresses to OA (Audenaert et al., 2011; Clohisy et al., 2009). Although this damage can occur in isolation, recent studies have found that the majority of the investigated cases have evidence of mild bone abnormalities (May et al., 2007; Peelle et al., 2005; Wenger et al., 2004; Wyss et al., 2007). These deformities can occur on either the pelvic or femoral side or a combination of both and involve minor variations in the orientation and shape of the acetabulum or femoral head-neck junction (Buller et al., 2012; Guanche and Bare, 2006; Köhnlein et al., 2009). These minor morphological abnormalities reduce the amount of clearance between the femoral neck and acetabular rim, as Figure 1.1 shows (Kubiak-Langer et al., 2007). This results in repetitive early contact between these osseous prominences particularly during end range of motion activities which cause both labral and prearthritic chrondral damage which if left untreated eventually progresses to OA (Almoussa et al., 2011; Tannast et al., 2007b). The combination of repetitive microtrauma which occur during end range of motion make the young active adult vulnerable to early OA of the hip (Guanche and Bare, 2006; Neumann et al., 2009).

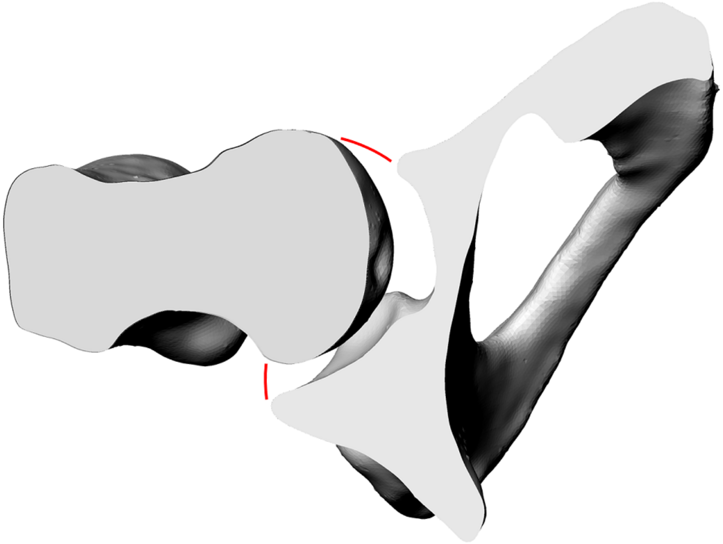
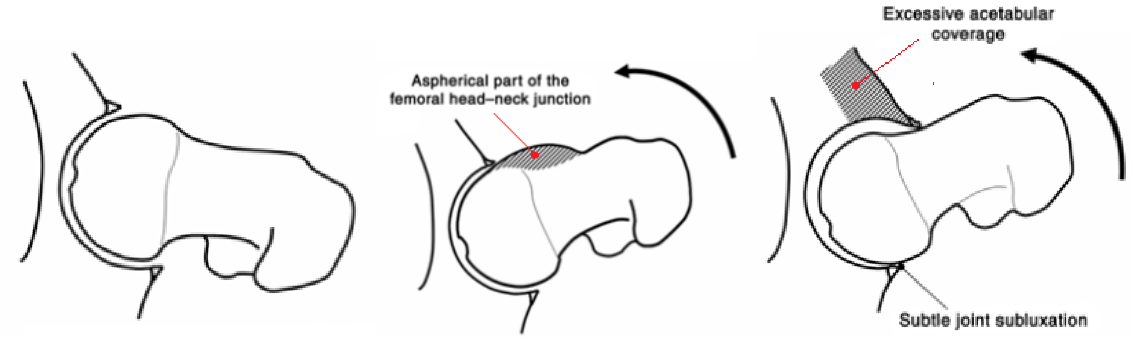


Figure 1.1: Illustration of joint clearance between the proximal femoral head-neck junction and pelvic acetabular rim.

FAI has been categorised into cam, pincer and mixed-type morphologies. Cam-type FAI occurs on the femoral side and appears as a cam-shaped abnormality at the femoral head-neck junction (Audenaert et al., 2011; Neumann et al., 2009). Cam impingement is caused by jamming this aspheric portion of the femoral head into the acetabulum (Ganz et al., 2008; Tannast et al., 2008). It typically occurs during flexion combined with additional rotation of the hip which induces compression and shear stresses at the labrum-cartilage junction and at the subchrondral bone of the acetabulum (Arbabi et al., 2010; Audenaert et al., 2011; Neumann et al., 2009). The ability of the cam-type prominences to intrude into the hip joint rather than abut against the acetabular rim means that they have a particularly destructive effect (Audenaert et al., 2011; Ganz et al., 2008). Damage typically occurs on the acetabular side in the anterosuperior quadrant and is often seen in young athletic males (Cobb et al., 2010; Ganz et al., 2003).

Pincer FAI occurs on the acetabular side and appears as either a focal or a general overcoverage of the femoral head by the acetabulum (Cobb et al., 2010; Tannast et al., 2007b). A focal overcoverage is caused by a retroverted acetabulum while a general overcoverage is the result of a deep acetabulum (Beck et al., 2005; Pfirrmann et al., 2006). In end range of motion activities this overcoverage causes early abutment of the femoral neck against the acetabular rim (Audenaert et al., 2011; Ganz et al., 2008). This leverage effect causes anterior labral damage and posterior wear which is typically less extensive than cam-type impingement (Cobb et al., 2010; Ganz et al., 2008; Neumann et al., 2009). Therefore, joint degeneration is a slower process and typically occurs in middle aged



(a) Normal hip joint. **(b)** Cam-type impingement. **(c)** Pincer-type impingement.

Figure 1.2: Illustration of femoroacetabular impingement (Tannast et al., 2007a).

women who perform high demand activities (Ganz et al., 2008). It has traditionally been regarded that isolated cam-type or pincer type impingement is rare, most patients will have a combination of these two conditions (Ganz et al., 2008; Neumann et al., 2009). However, recent studies have regarded these two mechanisms to be distinct (Cobb et al., 2010; Laborie et al., 2011). Figure 1.2 illustrates a normal hip joint in contrast to hips displaying either cam or pincer type impingement.

2 Clinical presentation of femoroacetabular impingement

Treatment of FAI can be difficult as the onset of symptoms are often subtle and unnoticed by the patient (Arbabi et al., 2010; Murphy et al., 2004). Initially, they notice limited range of motion during sporting activities - such as skiing or swimming (Tannast et al., 2007a; Wyss et al., 2007). It is only when they are regularly participating in sports, particularly stop and go activities like soccer, hockey, hand ball and tennis that there is a slow onset of groin pain which typically starts after minor trauma (Ganz et al., 2003; Wyss et al., 2007). Patients will experience pain intermittently at first, typically after sporting activities or being seated for a prolonged period (Ganz et al., 2003; Tannast et al., 2007a). Patients will then seek medical consultation presenting with a degree of functional impairment in conjunction with groin pain (Jung et al., 2011; Leunig et al., 2009). There are other pain and functional symptoms such as trochenteric pain radiating in the lateral thigh or experiencing pain when putting on ones shoes (Clohisy et al., 2009; Tannast et al., 2007a). Figure 2.1 shows the typical location and frequency of pain for patients with FAI.

A recent study by Gosvig et al. (2010) analysed the responses given by 3,620 subjects (1,332 male, 2,288 female) to the question *“have you experienced frequent or recurrent deep deep pain in the groin during the last 12 months?”*. It was found that it was not only subjects with FAI that experienced groin pain but also patients with developmental abnormalities such as DDH and those patients without any malformations. In fact, patients with hip abnormalities did not have higher incidence of groin pain compared with normal hips. This the author’s suggest shows that groin pain is a limited predictor of hip joint malformation, making prompt diagnosis difficult (Gosvig et al., 2010). Clohisy et al. (2009) found that patients had to wait on average three years, seeing on average 4.2 healthcare providers, before a correct diagnosis of FAI was made. This is because the symptoms overlap with other abnormalities of the hip and lumbar spine (Arbabi et al., 2010; Clohisy et al., 2009). There is one clinical examination that has been shown to be well correlated with a diagnosis for FAI and that is to test for the impingement sign. 88% to 99% of patients diagnosed with FAI have a positive impingement sign (Clohisy et al., 2009; Leunig et al., 1997; Philippon et al., 2007). Anterior FAI, where impingement typically occurs in the anterosuperior quadrant of the acetabulum can be diagnosed upon physical examination if there is reproducible pain when the hip is flexed at 90^o and then internally rotated or both internally rotated and sligtly adducted (Tannast et al., 2007a; Lamontagne et al., 2009). Forced internal rotation induces shearing forces at the labram which creates pain at the site of the labral or chondral lesion (Ganz et al., 2003). This recreates the pain experienced during daily activities for patients with cam-type impingement. Forced flexion with internal rotation squeezes the aspheric part of the femoral head into the actabulum, producing an ‘outside-in’ abrasion of the acetabular cartilage and potential tearing of the

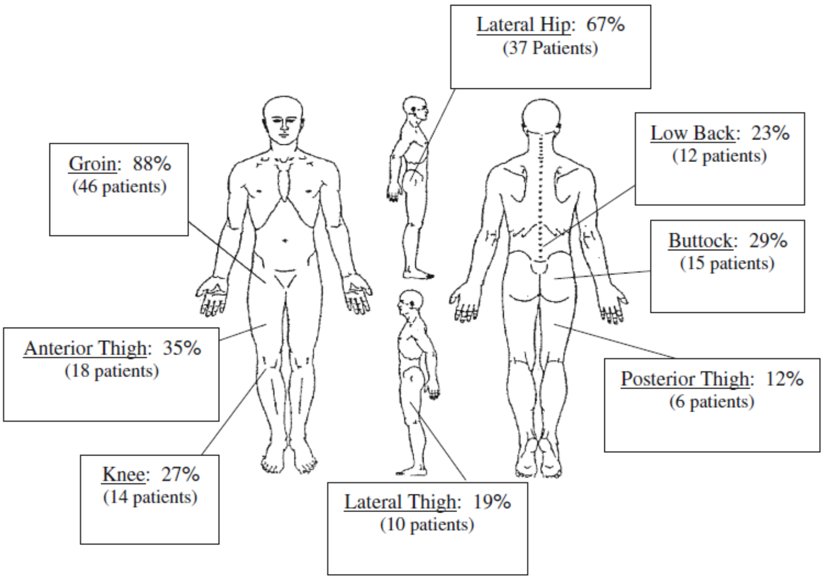


Figure 2.1: Location and frequency of pain for patients with femoroacetabular impingement (Clohisy et al., 2009).

labrum in the anterosuperior rim of the acetabulum (Dudda et al., 2009; Lamontagne et al., 2009).

Occasionally with pincer-type FAI there is posteroinferior impingement where the femoral neck leverages on the front of the acetabulum causing posterior wear in what it known as the contre-coup lesion (Cobb et al., 2010; Ganz et al., 2008). This can be recreated by externally rotating the leg in extension giving rise to deep seated groin pain (Tannast et al., 2007a). If while flexing the leg there is unavoidable passive external rotation this indicates presence of a SCFE in what is known as a positive Drehmann sign (Kamegaya et al., 2011; Tannast et al., 2007a). Figure 2.2 provides an illustration of these clinical tests.

FAI as a clinical diagnosis is estimated to exist within 10-15% of the adult population (Laborie et al., 2011; Tannast et al., 2007a). Typically they tend to be highly active with over 50% participating in regular sporting activities and 29% characterising their activity level as high (Clohisy et al., 2009). This indicates that high demand activity is a risk factor for the development of symptomatic FAI (Clohisy et al., 2009; Ito et al., 2001). Consequently, there may be many more people with subtle bone abnormalities that remain asymptomatic because they do not routinely participate in activities that demand forced flexion and internal rotation (Wyss et al., 2007). Further there may be some activities that require great flexibility and consequently are unsuitable for individuals with mild or severe deformities (Wyss et al., 2007). In addition, subjects may also be symptomatic but may not exhibit characteristic subtle bone abnormalities. Typically these patients are hypermobile and exihibit pincer-type impingement, an example of this type of individual is a female

(a) Anterior impingement. **(b)** Posteroinferior impingement. **(c)** Drehmann's sign.

Figure 2.2: Clinical tests to assess femoroacetabular impingement (Tannast et al., 2007a).

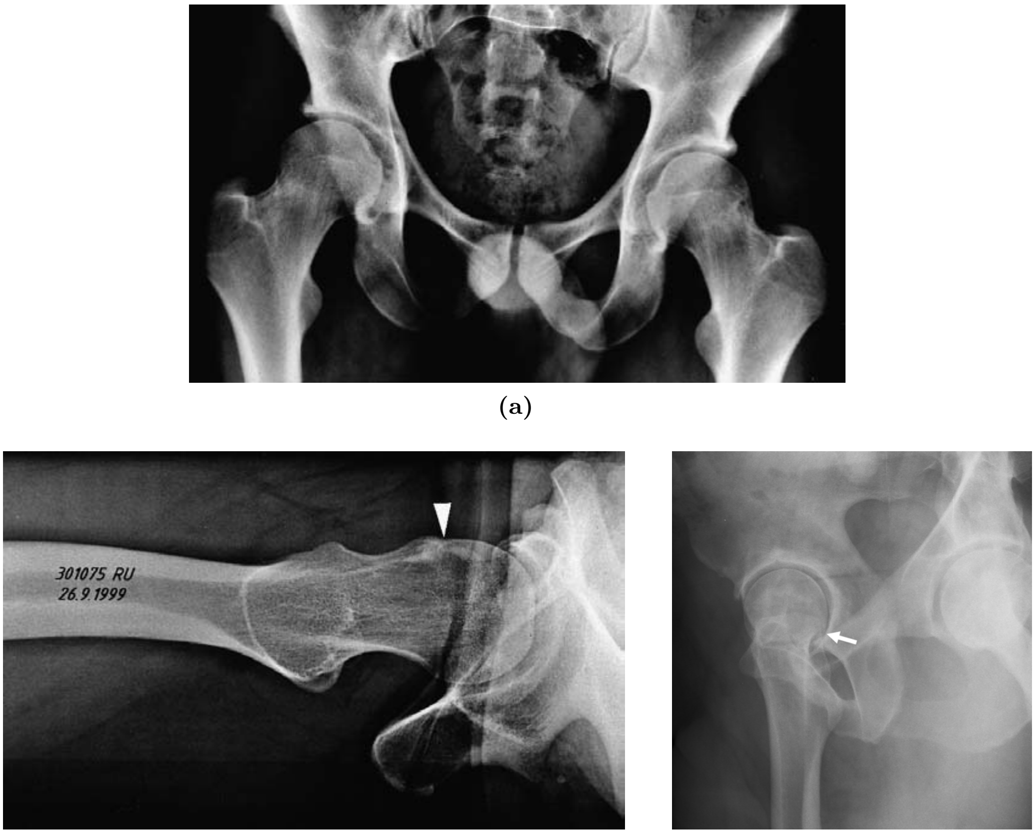
ballet dancer (Tannast et al., 2007a). The link of activity with symptomatic FAI explains why patient's will fail conservative treatment. FAI is a mechanical problem therefore conservative treatments such as anti-inflammatory medications and activity modifaction will not eliminate the source (Guanche and Bare, 2006). In a number of cases where restricted range of motion is being treated by stretching. Patients with FAI will often fail this treatment approach and may even come to harm (Guanche and Bare, 2006; Wyss et al., 2007).

After clinical examination where the patient exhibits a positive impingement sign there are a number of radiograph measures which can be used to diagnose the type of FAI and its severity. These radiographic measures are considered in the following section.

3 Diagnostic imaging

There are a number of imaging modalities that can be use to diagnose and assess FAI. Radiographs are used to make an assessment of the femoral head-neck junction and the contour of the acetabular rim (Laborie et al., 2011). Magnetic Resonance Imaging (MRI) or more typically Magnetic Resonance Arthrography (MRA) is used to assess soft tissue damage (Leunig et al., 2004; Siebenrock et al., 2003). However, both Magnetic Resonance (MR) and Computer Tomography (CT) imaging are now being used to gain a three-dimensional understanding of the bone (Beaulé et al., 2005; Jung et al., 2011). It has been acknowledged that radiographs cannot assess the full extent of the asphericity of the femoral head-neck junction as its maximum aspheric deviation occurs in the anterosuperior quadrant which is common blindspot radiologically (Leunig et al., 2009; Jung et al., 2011). Dudda et al. (2009) found in their study that asphericity of the femoral-neck junction when assessed radiographically would have been underestimated in 34.6% of cases. However, there are still drawbacks with both MR and CT imaging. CT requires a rather high dose of radiation and can only provide a suitable evaluation of the bony anatomy (Leunig et al., 2009). While MRA is accurate at assessing the integrity of the labrum, for identification of adjacent acetabular cartilage disorders it is less reliable (Heyworth et al., 2012; Siebenrock et al., 2003). However, future developments in MR technology may add to the image quality particulary for visualisation of the bony contour, cartilage lesions and capsular adhesions (Leunig et al., 2009).

There are a number of common radiographic projections which are use to diagnose FAI, Figure 3.1. Among these views, the standard projections are the Anteroposterior (AP) radiograph and the Axial Cross-Table radiograph (Tannast et al., 2007a). The AP projection provides a view of the lateral femoral head-neck junction while the cross-table view provides a view of the anterior aspect of the hip joint (Ganz et al., 2008). A frog-leg radiograph is another projection which is commonly used to assess the lateral aspect of the femoral head-neck junction as well as the focal prominence of the acetabular rim (Laborie et al., 2011). An alternative to the cross-table view is the Dunn-Rippstein projection which is taken with the leg flexed to 45^o to show the anterior of the femoral head-neck junction (Tannast et al., 2007a). A false-profile view is occasionally used to assess anterior acetabular over-coverage (Tannast et al., 2007a). In summary, a lateral and anterior view of the femoral head-neck junction and acetabular rim is sought. These radiographs first allowed a number of measurements to be made to assess the extent of the bone abnormality, such as centre-edge angle, acetabular centre margin angle, femoral head coverage, acetabular index, extrusion index, α angle and femoral head aspherity (Cobb et al., 2010). These different projectional measurements will be presented in section 3.1 and 3.2 for the proximal femur and acetabulum respectively.

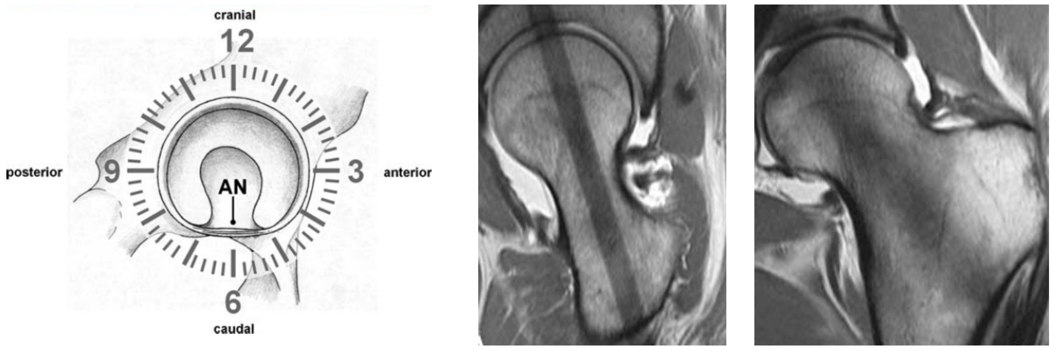


(a)

(b)

(c)

Figure 3.1: Common radiographic projections **(a)** Anteroposterior radiograph - taken with the leg in neutral flexion and internally rotated by 15^o to bring the femoral neck axis in line with the coronal plane to provide full view lateral aspect of the femoral head-neck junction, x-ray beam parallel to the coronal plane **(b)** Axial cross-table radiograph - taken in supine position with leg in neutral flexion and in either neutral rotation or internally rotated by 15^o, x-ray beam directed to the inguinal fold **(c)** False profile view - to assess anterior acetabular overcoverage (Ito et al., 2001; Maruyama et al., 2001; Neumann et al., 2009; Tannast et al., 2007a).



(a) **(b)** **(c)**

Figure 3.2: MR radial slices **(a)** Illustration of clockwise MRI slices **(b)** MR slice at the 3 o'clock position **(c)** MR slice as the 12 o'clock position (Dudda et al., 2009; Tannast et al., 2008).

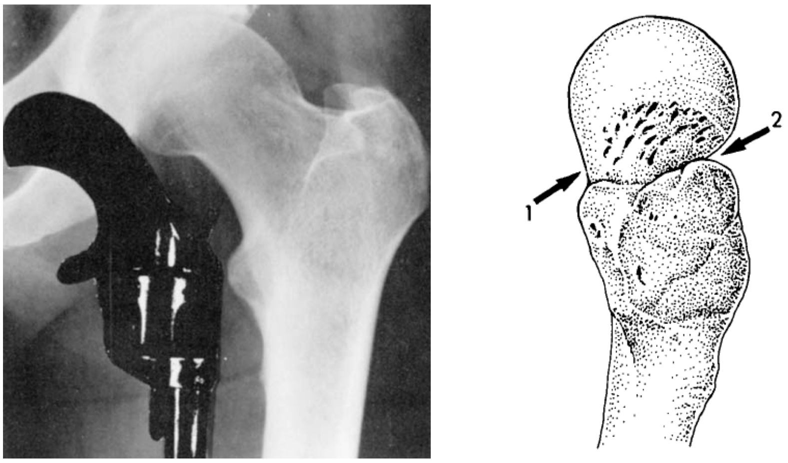
As well as radiographic projections, there are also common CT and MR views. For instance, the coronal scout view provides an image which corresponds to a lateral radiograph and is parallel to the axis of the femoral neck which passes through the centre of the femoral head (Notzli et al., 2002). However, both imaging modalities have the ability to provide non-standard radial sequences where images are taken about the femoral neck axis in both orthogonal and oblique planes as Figure 3.2 show (Dudda et al., 2009; Rakhra et al., 2009).

An overview of the image modalities used to diagnose FAI has been provided. Sections 3.1 and 3.2 will now provide an overview of the clinical measurements taken using these modalities to assess the extent of the bone abnormality for both the proximal femur and acetabulum.

3.1 Femoral assessment

There are number of radiological and imaging measures used to diagnose a cam-type deformity or assess its severity. These measurements include the α angle, β angle, anterior offset and triangular index (Gosvig et al., 2007; Ito et al., 2001; Notzli et al., 2002; Wyss et al., 2007). These measurements are used to quantify osseous bump formation on the femoral head-neck junction whose appearance signifies cam pathology (Tannast et al., 2007a). The orientation of the proximal femoral neck can also cause cam-type impingement which is assessed using the traditional anatomical measurements of the Caput-Collum-Diaphyseal (CCD) angle or neck-shaft angle and femoral anteversion (Murphy et al., 1987; Widmer and Majewski, 2005).

The α angle is perhaps the most widely used measure to assess the extent of the osseous bump formation at the femoral head-neck junction. It was defined by Notzli et al. (2002) to provide a quantifiable assessment of descriptions such as 'pistol-grip' (Stulberg et al.,

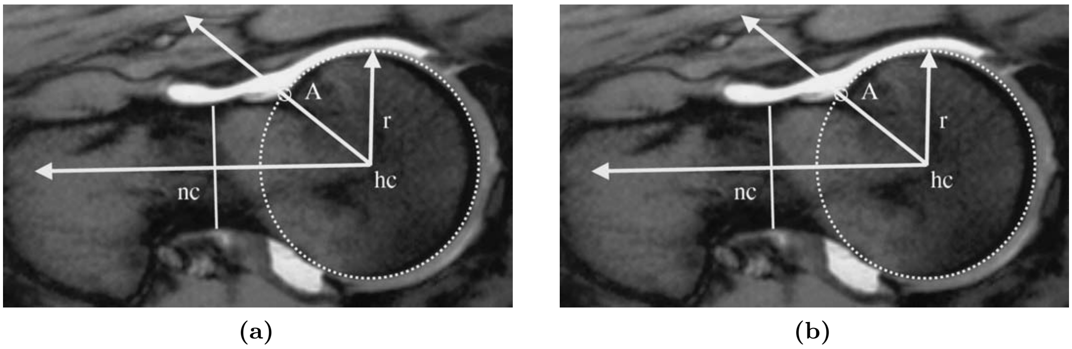


(a) **(b)**

Figure 3.3: Cam pathology **(a)** Pistol-grip deformity (Stulberg et al., 1975) **(b)** Mild post-slip deformity which shows loss of concavity of the femoral head-neck junction at point (1) and increased concavity at point (2).

1975) and 'post-slip' (Goodman et al., 1997) which had been used previously to describe the osseous bump formation in pathological cam-type impingement. Stulberg et al. (1975) described a flattened femoral head-neck junction seen on AP radiographs being present in 40% of patients who develop OA of the hip. Goodman et al. (1997) also described a flattened femoral head-neck junction but in the anterior aspect of the proximal femur which AP views may miss. This flattened morphological shape in both cases is thought to be characteristic of a silent post-slipped capital femoral epiphysis (Ganz et al., 2008; Goodman et al., 1997). Figure 3.3 shows the loss of concavity of the femoral head neck junction in both the superior and anterior aspects and is why both AP and axial cross-table radiographs are taken to diagnose FAI (Tannast et al., 2007a).

Notzli et al. (2002) compared 39 patients with symptomatic groin pain with 35 asymptomatic control subjects. The purpose of the original study was to confirm that young patients with clinical signs of impingement also had shape abnormalities at the anterior of the femoral head-neck junction (Notzli et al., 2002). Therefore, axial MRI images were acquired whereby the projection image was adjusted to be parallel to the individual patient femoral neck axis passing through the centre of the femoral head. This oblique axial plane was defined using a coronal scout view whereby the angle of the femoral neck axis could be defined (Notzli et al., 2002). Figure 3.4, shows the measurement of the α angle using the axial MRI image. Using this figure, the α angle is measured from a line (nc-hc) defined by the centre of the femoral neck at its narrowest point and the femoral head centre (hc) to a line (A-hc) where point (A) is the position at which the surface of the femoral head (A-hc) first exceeds the radius (r) of the cartilage covered area (Notzli et al., 2002). It is regarded



(a) **(b)**

Figure 3.4: Measurement of α angle for **(a)** normal subjects *and* **(b)** patients with cam-type pathology.

that hips with a deformity of the femoral head neck junction have a large α angle. This will be discussed further in section 4 (Jung et al., 2011; Neumann et al., 2009; Notzli et al., 2002).

The measurement of α angle described by Notzli et al. (2002) assessed the severity of the anterior femoral head-neck deformity which was measured in an oblique axial plane. However, both Gosvig et al. (2007) and Jung et al. (2011) measured α angle in the coronal plane using AP radiographs and coronal scout CT images respectively. These studies confirmed the presence of osseous bump or 'pistol grip' formation in this view. The studies of Dudda et al. (2009) and Rakhra et al. (2009) measured α angle using the radial images as illustrated in Figure 3.2. Both studies found that the maximum α angle occurs anterosuperiorly in the 1 o'clock to 2 o'clock position (Dudda et al., 2009; Rakhra et al., 2009). Therefore, three-dimensional assessment is more sensitive in assessing FAI than using plain radiographs, coronal scout views or oblique axial images alone. Dudda et al. (2009) found that asphericity of the femoral head-neck junction would have been underestimated in 34.6% of patients. Rakhra et al. (2009) found that 54% of subjects with a non-pathological α angle in the oblique axial plane were in fact pathologic when measured in a radial plane. Consequently, a substantial portion of subjects with a seemingly normal femoral head-neck contour may in fact be pathogical (Rakhra et al., 2009).

Both Beaulé et al. (2005) and Wyss et al. (2007) have described β angle measurement. These are two different types of measurement. In the Beaulé et al. (2005) definition the β angle is a mirror image of the α angle whereby it assesses posterior concavity of the femoral head-neck junction as opposed to the anterior concavity. Using Figure 3.3b, cam-type impingement causes a loss of anterior concavity shown at point 1 and an increase in posterior concavity shown at point 2. Therefore, a patient with cam-type impingement should have a larger α angle and smaller β angle than a normal subject. Consequently Beaulé et al. (2005) found that the α:β ratio was more sensitive at diagnosing cam-impingement than α

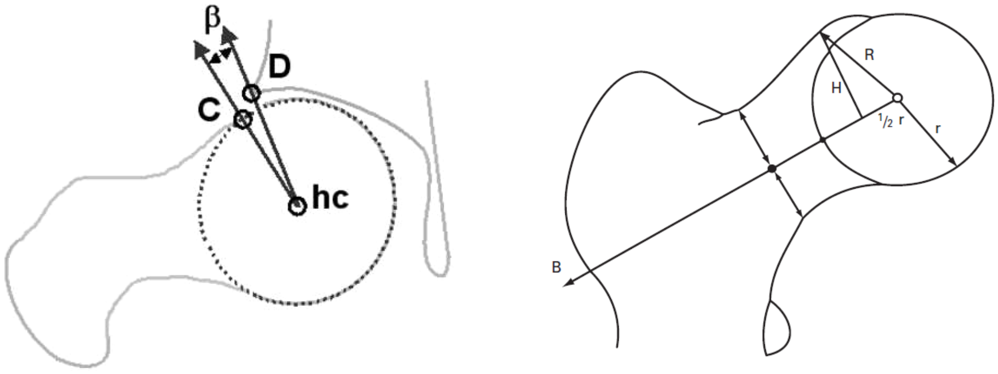
angle alone. However, these measurements were performed using planar reformation of the axial oblique plane using CT imaging. In three-dimensional imaging the β angle would be the α angle measurement for the posterior radial slice. However, the ratio can still be applied in the diagnosis of FAI.

Wyss et al. (2007) used the term β angle to describe the clearance between the femoral head-neck junction and the acetabular rim. It therefore considers the effect of both cam-type and pincer-type morphology. This angle was measured in an axial plane where the space between the acetabular rim and the femoral neck was at its smallest. The β angle as defined by Wyss et al. (2007) is shown in Figure 3.5a. Similar to the α angle point C represents the point where the concavity of the anterior femoral head is lost, while point D is the lateral bony margin of the acetabulum (Wyss et al., 2007). The angle formed between the lines (hc-C) and (hc-D) is defined as the β angle. The measured β angle is dependent upon the relative orientation of the proximal femur with regard to the acetabulum. Consequently, its result will change in accordance to the posture of the subject. Wyss et al. (2007) used this to determine whether clinically replicated groin pain when the hip is flexed at 90^o and then internally rotated correlated with small β angle clearance when the hip was flexed at 90^o. This will be discussed further in section 4.

Gosvig et al. (2007) extended the findings of Notzli et al. (2002) with regard to their measurement of both α angle and offset to develop the triangular index. The measurement of the triangular index is shown in Figure 3.5b where (r) is the natural radius of the femoral head. At a distance ${}^{r}/_{2}$ along the femoral neck axis, the distance (H) is measured perpendicularly from the femoral neck axis to the border of the femoral head neck junction. The radius (R) from this point to the centre of the femoral head (hc) can be calculated using Pythagoras theorem for right handed triangles ($a^2 + b^2 = c^2$). Consequently, if (R) is greater than (r) than this represents a loss of concavity of the femoral head-neck junction symptomatic of cam impingement. Gosvig et al. (2007) found that the α angle and the triangular index were highly inter-related. However, the α alpha was more sensitive to the internal/external rotation of the femur, where as the triangular index value remains relatively unaltered with rotation of the femur.

The final measurement used to assess the extent of osseous bump formation is femoral offset. There are a number of definitions of femoral offset (Eijer et al., 2001; Ito et al., 2001; Notzli et al., 2002). These methods quantify the linear distance between the femoral neck radius and the femoral head radius and has been measured on AP and lateral crosstable radiographs (Beck et al., 2005; Tannast et al., 2007a). Ito et al. (2001) extended this method to take points around the femoral head and neck circumference.

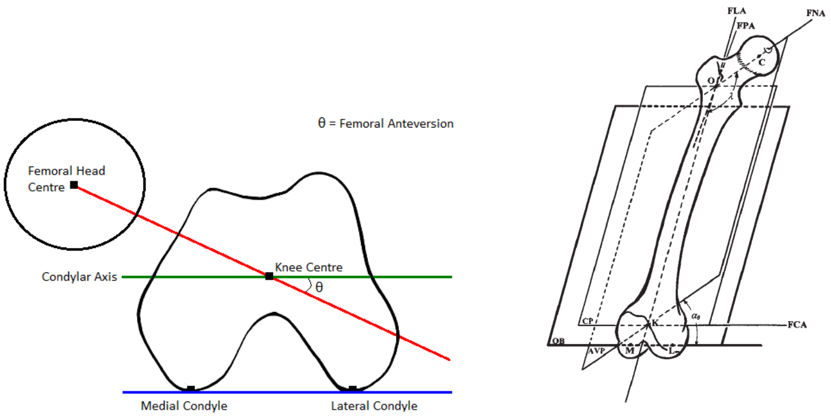
As well as measurements which quantify the osseous bump formation on the femoral head-neck junction. The orientation of the femur can also cause cam-type impingement. The



(a) **(b)**

Figure 3.5: Measurement of osseous bump formation using **(a)** β angle (Wyss et al., 2007) *and* **(b)** Triangular index (Gosvig et al., 2007).

orientation of the femur is defined by measurement of femoral anteversion and neck-shaft angle. Femoral version, in a joint coordinate frame is regarded to be the angle between the femoral neck axis and the coronal plane (Ko and Yoon, 2008; Seki et al., 1998; Yoshimine, 2006). It has been defined clinically by Murphy et al. (1987) as the angle between the femoral neck axis and an axis parallel to the posterior aspect of the femoral condyles, measured in the transverse plane. This axis is known as the condylar axis and is shown in Figure 3.6a. The condylar axis is used to define the neutral rotation of the femur. Therefore, it is coincident with the coronal plane of the hip joint (Maruyama et al., 2001). The femoral neck-shaft angle is defined as the angle between the femoral neck axis and the longitudinal axis of the femur, shown as symbol λ in 3.6b (Maruyama et al., 2001).



(a) **(b)**

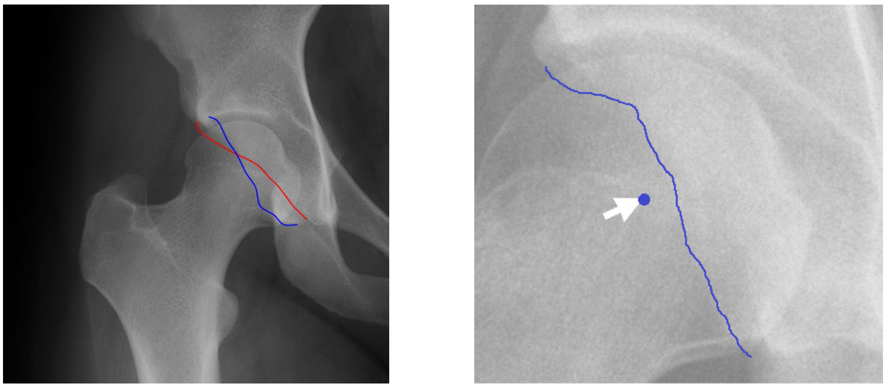
Figure 3.6: Measurement of femoral orientation **(a)** Femoral anteversion (Murphy et al., 1987) *and* **(b)** Femoral neck-shaft angle (λ) (Maruyama et al., 2001).

3.2 Acetabular assessment

Similar to cam-type impingement there are a number of radiological measurements which are used to diagnose and assess pincer morphology. As discussed in section 1 pincer-type impingement occurs when there is direct linear abutment between the proximal femoral neck and the acetabular rim, which is caused by either a focal or generally overcovered acetabulum (Beck et al., 2005; Neumann et al., 2009). It is hypothesised that this is a result of an unrecognised mild developmental dysplasia which causes acetabular cartilage damage in a thin circumferential strip adjacent to the labrum as well as the contre-coup lesion (Ganz et al., 2008; Tannast et al., 2007a). Focal overcoverage is thought to be a result of acetabular retroversion where the anterolateral edge of the acetabulum obstructs motion (Siebenrock et al., 2003). A globally overcovered acetabulum is a result of a deep acetabulum diagnosed as protrusio acetabuli or coxa profunda (Gosvig et al., 2010; Neumann et al., 2009). In both cases the leverage effect caused by early abutment means that pincer hips typically fail toward a posteroinferior of central OA (Ganz et al., 2008).

Both focal and global overcoverage in pincer-type impingement is principally diagnosed from AP radiographs using two measures - the crossover sign and the posterior wall sign (Laborie et al., 2011; Siebenrock et al., 2003). Clohisy et al. (2008) stated that the presence of the crossover sign in combination with a deficient (positive) posterior wall sign was indication of acetabular retroversion, while the presence of the crossover sign alone indicated anterior overcoverage. A prominent posterior wall (negative sign) is generally seen with coxa profunda or protrusio acetabuli in a globally overcovered acetabulum. However, it can appear in isolated cases of posterior focal overcoverage, as opposed to the more common anterior overcoverage (Tannast et al., 2007a). A positive crossover sign occurs when the anterior acetabular rim border is more lateral than the posterior rim in the cranial part of the acetabulum (Cobb et al., 2010; Tannast et al., 2008). In normal cases the outline edges of the anterior and posterior wall borders should meet superiorly and laterally (Taunton, 2007). However, the crossover sign appears when the anterior border crosses over the posterior border medial to the lateral edge of the acetabulum (Beck et al., 2005; Taunton, 2007). Considering the posterior wall sign, in a normal hip the posterior wall border should descend through the centre of the femoral head (Tannast et al., 2007a). If the posterior rim border lies medially to the centre of the femoral head, then this is indication of a deficient posterior wall (Clohisy et al., 2008). Both a positive crossover and posterior wall sign are shown in 3.7.

Global overcoverage is diagnosed on an AP radiograph by either coxa profunda or protrusio acetabuli which indicates a deep acetabulum (Tannast et al., 2007a). The degree of overcoverage can be quantified using the lateral centre edge angle, anterior centre edge angle, femoral head extrusion index and the Tönnis angle (Clohisy et al., 2008). These



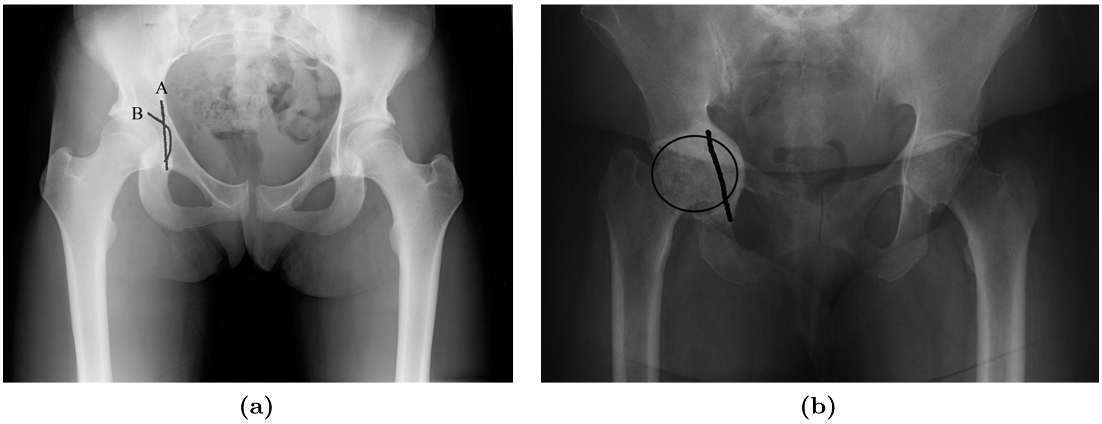
(a) (b)

Figure 3.7: Diagnosis of acetabular retroversion or focal overcoverage **(a)** Crossover sign (Taunton, 2007) *and* **(b)** Posterior wall sign (Laborie et al., 2011).

are traditional measures which have been used in the assessment of acetabular dysplasia (Clohisy et al., 2008). A coxa profunda is diagnosed using an AP radiograph when the floor of the acetabulum touches or overlaps the ilioischial line medially (Beck et al., 2005). A protrusio is diagnosed when the femoral head overlaps the ilioischial line medially (Beck et al., 2005). Both these cases are shown in Figure 3.8, a normal hip will have the acetabular fossa lying laterally to the ilioischial line (Tannast et al., 2007a).

The lateral centre edge angle is one of the predominant methods of quantifying acetabular overcoverage. The angle is formed by a vertical line and a line which connects the centre of the femoral head with the lateral edge of the acetabulum. If the angle is greater than 39^o then the hip is overcovered, if it is less than 25^o the hip is dysplastic (Tannast et al., 2007a). The anterior centre edge angle is calculated using a false profile view in the same manner as the lateral centre edge angle (Clohisy et al., 2008). The femoral head extrusion index determines the percentage of the femoral head which is not covered by the acetabulum and should normally be less than 25% (Tannast et al., 2007a). Finally, the Tönnis angle is the angle formed on an AP radiograph between a horzontal line drawn from the inferior sourcil and a line connecting the interior sourcil with the lateral sourcil (Clohisy et al., 2008). In a normal hip this angle should be between 0^o and 10^o but in hip with coxa profunda or protrusio it is 0^o or negative (Clohisy et al., 2008; Tannast et al., 2007a). These measurements are very dependent upon pelvic orientation as the vertical and horzontal lines used as the datums from which to calculate many of these angles should be aligned with an anatomical axis (Köhnlein et al., 2009; Siebenrock et al., 2003).

CT imaging has allowed the coverage of the acetabulum to be quantified in three-dimensions (Cobb et al., 2010; Murphy et al., 1990). Where sections along the acetabular rim are measured relative to a polar axis. The polar axis is formed by taking points along the



(a) (b)

Figure 3.8: Diagnosis of a deep acetabulum **(a)** Coxa profunda *and* **(b)** Protrusio (Clohisy et al., 2008).

rim of the acetabulum and best-fitting a plane to these points, known as the acetabular rim plane (Cobb et al., 2010). The normal to this plane is defined as the polar axis and is located at the hip joint centre. This polar axis can be used to define the acetabular inclination and anteversion relative to the pelvic coordinate frame typically derived from the Anterior Pelvic Plane (APP) using the definitions of Murray (1993). The hip joint centre is the centre of a best-fit sphere formed from points taken from the articular surface of the acetabulum (Cobb et al., 2010). The coverage angle is the angle between the polar axis pointing medially from the hip joint centre and a line joining the hip joint centre with an individual acetabular rim point (Cobb et al., 2010; Murphy et al., 1990). A rim point is hemispherical when it is 90^o, undercovered when it is less than 90^o and overcovered when it is greater than 90^o (Murphy et al., 1990). These rim points are then transferred to a clockface for visualisation. Figure 3.9 illustrates the calculation of this acetabular coverage angle. However, as Köhnlein et al. (2009) identifies, the rim of the acetabulum is shaped in a regular wave form with three consistent prominences and two depressions. Consequently, the acetabular rim plane is artificial which may affect interpretation of the results, although its pattern is predictable (Cobb et al., 2010).

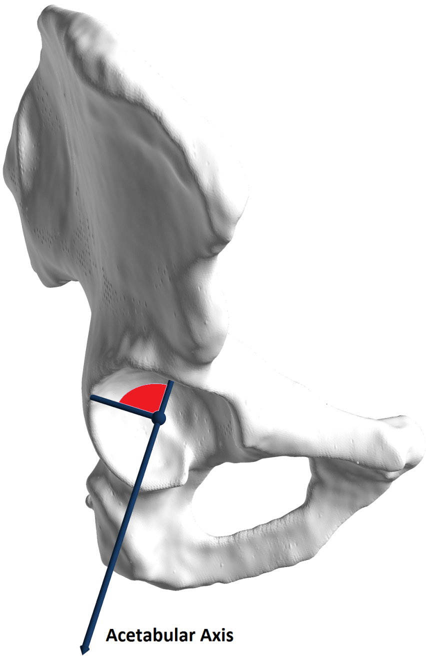


Figure 3.9: Three-dimensional calculation of the acetabular angle

3.3 Summary

This section has reviewed the predominant diagnostic measurements used to describe both the osseous abnormality and orientation of the acetabulum and femur. This will aid the analysis of the skeletal, radiographic, CT and MR studies which will be discussed in the following section. One of the most important factors that has arisen through the documentation of the various diagnostic measurements is the disconnect between two-dimensional and three-dimensional imaging. The various projection planes result in different interpretations of the diagnostic measurements and should be considered when analysing clinical studies. Many of the clinical studies discussed in the following section also consider the degree of OA that is evident in the joint. Predominantly, the degree of OA is evaluated using the Tönnis Grade (Clohisy et al., 2008).

- Grade 0: No radiological sign of OA.
- Grade 1: Increased sclerosis of the head and acetabulum, slight jointspace narrowing, and slight lipping at the joint margins.
- Grade 2: Small cysts in the head or acetabulum, moderate joint-space narrowing, and moderate loss of sphericity of the head.
- Grade 3: Large cysts in the head or acetabulum, joint-space obliteration or severe joint-space narrowing, severe deformity of the femoral head, or evidence of necrosis.

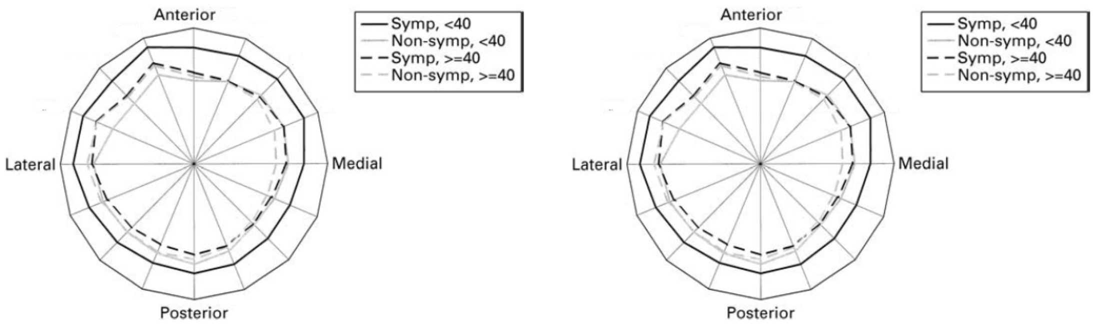
4 Radiographic findings

There have been a number of studies which have studied FAI morphology using standard radiographs, MR, CT as well as skeletal studies. This section will present the findings of these studies, which include assessment of osseous morphology and evaluation of joint degeneration. Firstly, femoral morphology will be discussed, followed by acetabular morphology and hip alignment. Finally, the link between abnormal hip morphology and OA will be considered.

4.1 Femoral morphology

One of the first quantitative studies which evaluated femoral morphology was the skeletal study of Goodman et al. (1997). The authors visually evaluated 2665 skeletons (2227 males, 438 females) for evidence of post-slip morphology, a total of 5330 hips. The study found that 306 (5.7%) of the femora analysed had evidence of a mild post-slip morphology, only 21 (0.4%) hips had a moderate or severe slippage. When comparing these 306 femora with age-matched femora with no evidence of post-slip morphology, significantly more of the mild post-slip femora (38% compared to 26%) had grade two or three OA (p-value ≤ 0.005). This difference was more pronounced in individuals aged 56 or older - 68% post-slip compared to 48% normal (p-value ≤ 0.025). The results of this study was one of the first to show that mild shape abnormalities of the proximal femur have an elevated risk of developing OA in comparison to normal hips. These mild post-slip abnormalities have the same epidemiological characteristics of femora associated with SCFE (Goodman et al., 1997).

Prior to the study of Notzli et al. (2002) which defined the radiological α angle measurement, Ito et al. (2001) sought to characterise the distribution and location of the osseous abnormality on the femoral head-neck junction. The authors used MR imaging and constructed a sagittal oblique plane with a view projecting along the femoral neck axis. Consequently, two sections were taken, one of the femoral head and the other of the femoral neck. Femoral head-neck offset was calculated using radial sections around these two planar images - comparing 24 (12 male, 12 female) symptomatic patients exhibiting a positive impingement sign with 24 asymptomatic volunteers. Femoral head-neck offset was significantly less within the patient group in the anterior to medial quadrant (p-value ≤ 0.05). Further, younger men had significantly less head-neck offset in the lateral and anterior aspects in comparison to age and gender match control subjects, particularly in the anterolateral region (p-value ≤ 0.001). These results are presented in Figure 4.1 which showed that patients appeared to have a shallower taper between the femoral head and neck making impingement possible within the normal range of motion. However, this



(a) **(b)**

Figure 4.1: Femoral head-neck offset ratio comparison **(a)** Symptomatic and non-symptomatic subjects **(b)** Age-matched male symptomatic and non symptomatic subjects (Ito et al., 2001).

impingement can only take place at a specific point in the arc of flexion which mean that both the level and type of activity play a role in the development of OA (Ito et al., 2001)

Siebenrock et al. (2004) assessed femoral head-neck offset in conjunction with measurement of epiphysial extension. The purpose was to assess the correlation between these two measurements, which if positive would support the hypothesis that decreased head-neck offset might be caused by a growth abnormality of the capital epiphysis. 15 patients with a hump malformation, normal acetabulum and a positive impingement sign were assessed in conjunction with 15 normal subjects. On comparison of the patient and the control groups there was a significantly decreased head-neck offset in the patient group. Patients also showed a significantly larger extension of the epiphysis onto the neck in this quadrant. These two measurement had a very high correlation coefficient supporting the hypothesis that a decreased head-neck offset is caused by a growth abnormality of the capital epiphysis.

The study by Notzli et al. (2002) was the first to define and measure the α angle using an oblique axial view to measure the aspherity of anterior aspect of the femoral head-neck junction. Beaulé et al. (2005) measured both the α and β angle in the same oblique axial plane to assess the aspherity of both the anterior and posterior aspects of the femoral head. Neumann et al. (2009) used cross-table radiographs to measure aspherity of the anterior aspect of the femoral head. Consequently, the α measurements of these studies can be compared in Table 4.1.

The α angle measurements are consistent among studies for both symptomatic and asymptomatic subjects. Neumann et al. (2009) has identified that since the study by Notzli et al. (2002), 55^o has been wrongly interpreted as the upper limit that allows for impingement free motion (Kubiak-Langer et al., 2007; Meyer et al., 2006). Neumann et al. (2009) also identified in their patient group that the average post-operative α angle of 43^o resulted in impingement free motion. This is because that impingement is caused by not only

Study	Symptomatic (α angle)	Asymptomatic (α angle)	p-value
Notzli et al. (2002)	74^o (55^o-95^o)	42^o (33^o-48^o)	$p \leq 0.001$
Beaulé et al. (2005)	66.4^o, (39^o-94^o)	43.8^o (39.3^o-48.3^o)	$p = 0.001$
Neumann et al. (2009)	66^o (45^o-79^o)		

Table 4.1: Comparison of anterior α angle measurements.

femoral head abnormality but also acetabular morphology, there is an interactive effect between the two. Therefore, in a normal hip an anterior α angle of 43^o may be sufficient for impingement free motion but in hips with a deep acetabulum it may be necessary to have an α angle of less than 43^o. The results of Neumann et al. (2009) also showed that the α angle remained stable one year after surgery - post-operatively 43^o (34^o-60^o) and at one year follow-up 41^o (34^o-51^o). In the study by Beaulé et al. (2005) they also noted that as well as the α angle being significantly larger in the patient group when compared to the asymptomatic control. In contrast, the β angle was significantly smaller in the patient group (mean 40.2^o) compared to the control group (mean 43.8^o). This agrees with the findings of Goodman et al. (1997) who found evidence that in a post-slip morphology there is a loss of concavity at the anterior of the femoral head-neck junction and an increase in concavity at the posterior of this junction, Figure 3.3b. Other notable findings were that the α:β ratio was more sensitive at diagnosing cam-impingement than α angle alone (81% compared to 72%) and that there was no correlation between age and α angle. It was also noted that within the symptomatic group males had a greater α angle than females - 73.3^o compared with 58.7^o. However, within the control group no such difference existed (Beaulé et al., 2005).

There are a number of studies which have used the α angle to quantify the asphericity of the femoral head-neck junction in the coronal plane using AP radiographs, thus evaluating pistol-grip morphology. Gosvig et al. (2007) analysed AP weight bearing radiographs of 2803 subjects (1055 male, 1748 female) in a population study. The authors found significant gender differences - the mean α angle for males was 52.4^o (30^o-100^o) for females it was 44.5^o (32^o-108^o). This was supported by detection of a hump malformation in 10% of males and only 2% of females. Consequently, the following pathological boundaries were defined: male - pathological ($\alpha \geq 83^o$), borderline ($69^o \geq \alpha \leq 82^o$) and normal ($\alpha \leq 68^o$), female - pathological ($\alpha \geq 57^o$), borderline ($51^o \geq \alpha \leq 56^o$) and normal ($\alpha \leq 50^o$). As well as a population study, Gosvig et al. (2007) also compared the α angle measurements in the coronal and axial views of 164 (82 male, 82 female) THA patients. For males the α angle was greater in the superior region 71^o (40^o-114^o) compared to 61^o (30^o-110^o) at the anterior. For females this difference was less pronounced - AP plane 59^o (39^o-103^o) compared to 57^o (27^o-106^o) in the axial plane. Consequently, the results of these α angle measurements in the AP plane reveal significant gender differences and that pistol-grip morphology is primarily a male condition. The study by Gosvig et al. (2007) is supported by the results presented by Jung et al. (2011) who assessed the prevalence of morphological abnormalities in asymptomatic adults. Jung et al. (2011) found that males had both a significantly greater α angle (59^o compared to 45^o) and a greater number of pathological (13.95% compared to 5.56%) and borderline (14.88% compared to 6.11%) cases in comparison to females (p-value ≤ 0.001). However, there were no significant differences in α angle between age groups within each gender challenging the assumption that FAI deformity develops over time.

Laborie et al. (2011) also assessed the prevalence of cam-type FAI in 60 eligible asymptomatic young adults (868 male, 1192 female) using lateral views of the hip. There were three indications of cam-type morphology - pistol grip (21.5% male, 3.3% female), focal prominence of the femoral neck (10.3% male, 2.6% female) and flattening of the lateral aspect of the femoral head (14.4% male, 6.2% female). Evidence of one of more of these cam features was shown in 304 males (35.0%) and 121 females (10.2%). This is similar to the number of borderline and pathological cases found in the study by Jung et al. (2011). This shows that the presence of asymptomatic cam-type deformity is not a rare condition especially within a healthy adolescent population (Laborie et al., 2011). Consequently, an abnormal α angle does not hold an absolute relationship with the presence of symptomatic disease (Jung et al., 2011).

The variation in the magnitude of the α angle around the circumference of the femoral head-neck junction has led researchers to take radial sections around the femoral head, as discussed in section 3.1. Pfirrmann et al. (2006) as part of their study measured the α angle at 8 radial sections around the femoral head in 50 patients (30 male, 20 female) average age 28.8 years (19-48). Of the 50 patients there were 33 patients diagnosed with cam impingement and 17 with pincer impingement. It was found that the α angle was significantly larger in the cam impingement group in the anterior (68^o compared to 54^o) and anterosuperior (81^o compared to 66^o) regions compared to the pincer group. Findings in the anterior region are consistent with those values presented in Table 4.1. However, the α angle was more pronounced in the anterosuperior region. These findings have been supported by both Dudda et al. (2009) and Rakhra et al. (2009) who both found that the maximum α angle occurred in the anterosuperior region. Consequently, many patients found not to be pathological using the traditional axial oblique plane and 55^o α angle limit were in fact pathological when radial images were analysed. As well as documenting measurements of femoral head-neck morphology in both symptomatic patients and asymptomatic subjects, other studies have looked at the damage patterns associated with cam-type impingement. Beck et al. (2005) analysed 26 (24 male, 2 female) pure pistol-grip deformities with damage to the labral, acetabular and femoral head cartilage, evaluated after surgical dislocation of the hip. In the cam-impingement group the labrum was separated from the cartilage in all 26 cases and damage to the acetabular cartilage was located anterosuperiorly in the one o'clock position. The mean depth of cartilage damage was found to be 11mm corresponding to one-third of the total depth of the cartilage at this location. Debonding of the acetabular cartilage from the subchondral bone was evident in 10 hips and more severe loss of fixation was found in a further 10 hips with frayed edges and cartilage thinning. Other studies have also noted soft-tissue damage associated with cam-type impingement. Siebenrock et al. (2004) noted that within their cohort of 15 patients, four had labral degeneration and 11 had partial labral tears. Philippon et al. (2012) during surgery of 65 hips (6 cam, 10 pincer, 49 mixed) had to address labral tears in all patients. Wyss et al. (2007) found that all patients had a degenerated or torn labrum and 86% had evidence of articular cartilage damage. Pfirrmann et al. (2006) assessed cartilage lesions and labral abnormalities in 33 cam patients and 17 pincer patients. Cartilage lesions were found in the anterior and anterosuperior quadrants and were significantly larger in the cam impingement group. Consequently, Pfirrmann et al. (2006) characterised cam FAI to include large α angles, acetabular cartilage lesions in the anterosuperior position and an osseous bump formation on the femoral neck.

4.2 Hip alignment and acetabular morphology

There have been a number of skeletal studies of pelvic morphology (Köhnlein et al., 2009; Maruyama et al., 2001). The study by Köhnlein et al. (2009) considered their findings in relation to FAI. They analysed 66 (42 male, 16 female, 8 unknown) acetabulae from 33 subjects and found that the outer bony rim was shaped in a regular wave-like manner with three consistent prominences and two depressions. The prominences were located in the anterosuperior, anteroinferior and posteroinferior regions of the acetabulum, while the depressions were located at the anterior wall and along the posterosuperior wall. The location and extent of these prominences and depressions were not distinguishable by gender. The anterior depression was on average 9^o below the level of a hemisphere while the posterosuperior depression was 21^o below the level of the hemisphere. The orientation of the acetabular opening plane was $48^o \pm 4^o$ in inclination, $21^o \pm 5^o$ in anteversion and $19^o \pm 6^o$ for tilt. Acetabular tilt describes the rotation of the acetabulum with respect to the APP plane, it is the angle in the sagittal plane between the APP and a line through the 6pm and 12pm positions of the acetabulum. The role of both acetabular inclination and tilt had not previously been considered with regard to FAI. Köhnlein et al. (2009) hypothesised that lower inclination was likely to decrease anterosuperior hip clearance which would lead to pincer impingement. In a similar manner decreased acetabular tilt would place the constant rim prominences more inferiorly causing decreased clearance. Consequently, the degree of pelvic tilt and acetabular tilt should be considered separately and further studies are needs to prove whether pincer FAI can result from the position of bony prominences in certain postures.

Buller et al. (2012) considered not only the alignment of the pelvis but also the femur. They hypothesised that acetabular retroversion may be compensated for by alterations in the proximal femur. The study determined the correlations between femoral version, neck-shaft angle, acetabular version, centre edge angle and gender in normal subjects - 115 patients (57 male, 58 female), average age 59 (29-75). Correlations were found between these anatomical measurements - a positive correlation between femoral version and acetabular version (0.38^o:1^o) and between femoral neck-shaft angle with acetabular version (0.21^o:1^o). The female gender was also positively correlated to both acetabular version (2.6^o:1^o) and centre edge angle (2.8^o:1^o). These findings build upon the results of Cobb et al. (2010) who found no significant difference in acetabular version between patients with cam or pincer FAI and control subjects with normal acetabulae. Indeed, Cobb et al. (2010) questioned whether acetabular retroversion was indeed a leading factor for FAI and in fact acetabular and femoral versions compensate for each other (Buller et al., 2012). Consequently, the authors suggest that improvement in FAI surgery may be due to addressing the labral tears and chrondral injury rather than correcting the bone abnormality. However, Ito et al. (2001) recorded in their study that femoral anteversion was significantly less in their patient group ($9.7^o \pm 4.7^o$) compared to the asymptomatic control ($15.7^o \pm 4.4^o$). This means as well as differences in acetabular orientation in FAI patients, femoral anteversion and neck-shaft angle my also be a route cause for impingement as well as bony morphology with regard to femoral hump malformation and acetabular overcoverage.

The combination of bony malformation, orientation of the acetabulum and proximal femur as well as pelvic tilt make it possible to experience impingement during a normal range of motion. One of the main manoeuvres which has been found to cause groin pain in symptomatic patients is forced internal rotation at 90^o flexion. Wyss et al. (2007) conducted a study to observe whether this manoeuvre correlated to lack of joint clearance at 90^o flexion. The study used positional MRI to image the subject at 90^o of hip flexion, there were 23 (19 male, 4 female) patients identified clinically with a positive impingement sign, average age 33 (22-42). There were 40 asymptomatic volunteers (20 male, 20 female), average age 30 (20-46). The β angle as described in section 3.1 was measured in the flexed position. There was a significant difference in both the measured internal rotation and β angle clearance between the patient group and the control group - patient group internal rotation 4^o (-10^o-20^o), β angle $5^o \pm 9^o$; control group internal rotation 28^o (10^o-40^o), β angle $30^o \pm 9^o$. The correlation between internal rotation and β angle clearance was $r = 0.97$. The results showed clinical evidence of hip impingement was due to direct abutment between the acetabular rim and femoral neck. Wyss et al. (2007), also found that internal rotation of less than 20^o was highly correlated to joint damage and anterior joint incongruity. They hypothesised that people with small β angle clearance could remain asymptomatic because they do not routinely participate in activities that demand forced flexion and internal rotation. In contrast, there may be some activities that are unsuitable for individuals with mild or severe deformities.

Cobb et al. (2010) analysed the extent of acetabular bony deformity in 20 normal subjects, 20 cam ($\alpha \geq 50^o$) and 20 pincer patients (lateral centre edge angle $\geq 39^o$). MRA was used to measure the acetabular angle in three-dimensions, as described in section 3.2 as well as the inclination and anteversion of the acetabular rim plane. It was found that on average cam acetabulae ($84^o \pm 5^o$) were shallower than normal hips ($87^o \pm 4^o$) which were shallower than pincer hips ($96^o \pm 5^o$) a one-way ANOVA statistic showed a significant difference between these groups. Considering, no significant difference was found with regard to acetabular inclination and anteversion, the only model for impingement in the pincer group was the depth of the acetabulum whereby overcoverage allows for linear abutment at the extremes of hip motion. These findings are supported by Pfirrmann et al. (2006) who also found that the acetabulum was significantly deeper in pincer patients with a mean depth of 4.8mm compared to 0.7mm in the cam impingement group.

In the normal population Laborie et al. (2011) found that overcoverage was evident in 14.4% of males and 4.9% of females. While evidence of focal overcoverage and acetabular retroversion was more prominent - posterior wall sign (23.4% male, 11.0% female) and crossover sign (51.4% male, 45.5% female). Evidence of one of more of these pincer features was shown in 298 males (34.3%) and 198 females (16.6%). There was a high degree of coexistance amongst most FAI findings but particularly with posterior wall sign and crossover sign especially within the female population. The presence of both these radiological signs indicates acetabular retroversion (Clohisy et al., 2008). Therefore, considering the commonality of pincer findings within the male population, acetabular retroversion in females may be the main cause of pincer-type FAI. Laborie et al. (2011) also found little overlap between cam and pincer findings which support the findings of Cobb et al. (2010) who regard cam and pincer deformities as distinct. Finally, the authors summarise that FAI indications are the result of anatomic variation rather than true pathologic abnormalities.

Considering the documentation of joint degeneration Beck et al. (2005) recorded labral as well as femoral and acetabular cartilage damage in 16 (2 male, 14 female) patients with isolated coxa profunda. In these hips, the labrum was separated from the acetabular cartilage in five hips. Damage to both the labrum and acetabular cartilage was more circumferential with a mean maximum depth of cartilage damage of 4mm at the 12 o'clock position. Loss of fixation of the acetabular cartilage was seen in five hips. Five hips had roughening of the acetabular cartilage in the posteroinferior region while ten femoral heads had posteroinferior cartilage damage - indicative of the contre-coup lesion (Ganz et al., 2003). These findings were reinforced by Pfirrmann et al. (2006) who analysed 17 patients with a deep acetabulum. In these hips, cartilage lesions were seen in the anterior and anterosuperior regions but significantly in contrast to cam hip, labral and cartilage lesions were also evident in the posterior and posteroinferior regions. Pfirrmann et al. (2006) characterised pincer FAI as having a deep acetabulum and posteroinferior cartilage lesions.

4.3 Association of radiological indications with osteoarthritis

A number of recent studies have been motivated by findings with regard to the prevalence of FAI morphology in the asymptomatic population to assess the link between FAI morphology and OA (Bardakos and Villar, 2009; Gosvig et al., 2010; Hartofilakidis et al., 2011). Bardakos and Villar (2009) built upon the findings of Wyss et al. (2007) who found when comparing patients with FAI and asymptomatic control subjects there was a 12% overlap in the range of internal rotation between the patients and the asymptomatic volunteers. Thus raising the question of how influencial the role of activity is in the development of systematic impingement. Bardakos and Villar (2009) hypothesised that not all hips with FAI were equally likley to develop FAI. To test this hypothesis they analysed the radiographs of patients who were under 55 with a pistol-grip deformity. Two sets of radiographs were analysed set 10 years apart for a total of 43 (47 hips) eligible patients. On the initial radiographs, 29 hips had mild grade I OA and 14 had moderate grade II OA. In the final radiographs a total of 28 hips had progressed to OA. There were three important factors which distinguished the OA group from the non-OA group - medial proximal femoral angle (p-value = 0.004), posterior wall sign (p-value = 0.02) and cross-over sign (p-value = 0.08). The medial proximal femoral angle describes the topographic relationship between the femoral head and greater trochanter in the coronal plane. Factors such as α angle, neck-shaft angle, centre-edge angle, Tönnis angle and coxa profunda were found not to be significant, although there was a low incidence of coxa profunda in the initial radiographs. The author's stated that their results show that mild to moderate OA of hips with a pistol grip deformity will not progress to full OA in all patients. In fact, other structural abnormalities such as acetabular version when present are partly responsible for this progress.

In a similar study, Hartofilakidis et al. (2011) sought to investigate the association of cam, pincer and mixed-type impingement and degeneration of the hip joint. The authors examined the initial AP radiographs of patients who had been treated for unilateral hip disease but on initial examination had no radiological signs of OA. A total of 96 (31 males, 65 females) patients were identified as having one or more morphologic features of FAI - pistol grip deformity, anterior rim prominence, posterior wall sign, α angle, centre edge angle, weight bearing surface, neck-shaft angle and crossover sign. Follow-up radiographs were also assessed for presence of early OA. Of the 96 hips there were 17 cam (1 developed OA), 34 pincer (7 developed OA) and 45 mixed (9 developed OA) - there was no significant difference in the incidence of OA amongst groups. The presence of the posterior wall sign together with crossover sign which indicate acetabular retroversion was significantly associated with development of OA. However, the study found that factors not measured by the study were significant contributors to the development of OA. Many authors cite that activity may play a role in the development of OA (Bardakos and Villar, 2009; Clohisy et al., 2009; Ito et al., 2001), while a recent study by Pollard et al. (2010) indicated that genetic influences may play a role. None of these factors were measured by the study.

The study by Gosvig et al. (2010) was a population based overview of the main osseous malformations of the hip seen radiologically. In total there were 3620 (1332 male, 2288 female) patients included in the study. The AP radiographs were reviewed and classified into (1) No malformation (2) acetabula dysplasia (centre edge angle $\leq 20^o$) (3) deep acetabulum in coxa profunda or protrusio acetabuli (centre edge angle $\geq 45^o$) (4) pistol-grip deformity (triangular index $\geq$ 0mm) and (5) a combination of a deep acetabulum and pistol-grip deformity. The prevalence of OA within the study group was found to be 9.5% in males and 11.2% in female. There was a significant correlation with prevalence of OA and patients with a deep acetabulum and pistol grip deformity. Of those patients with OA - 3.1% of males and 2.7% of females had acetabular dysplasia. A deep acetabulum was seen in 27% of males and 28.3% of females, a pistol-grip deformity in 30.2% of males and 5% of females. Finally, combined deep acetabulum and pistol grip deformity was present in 10.5% of males and 0.6% of females. The findings of this study reinforced previous findings in a number of areas. Firstly, it supports the findings of Goodman et al. (1997) who found that a pistol-grip deformity is primarily a malformation in males and the male to female ratio of this deformity is approximatley the same ratio found in cases of SCFE. The study also agreed with the findings of Goodman et al. (1997) with regard to pistol-grip being a significant risk factor for OA along with a deep acetabulum which has been found in other studies (Bardakos and Villar, 2009; Hartofilakidis et al., 2011). In fact the study found malformation in 71% of males and 36.6% of females with hip OA suggesting idiopathic OA has been overestimated in the past.

4.4 Summary

This section has summarised the findings of many of the significant studies analysing the predominance of FAI and its role in joint degeneration. The key findings of these studies have been summarised.

- Both Jung et al. (2011) and Laborie et al. (2011) have identified that both cam and pincer morphology is common in the asymptomatic population and the studies by Bardakos and Villar (2009), Gosvig et al. (2010) and Hartofilakidis et al. (2011) have analysed progression to OA in subjects with these morphologies. It has been found that presence of cam or pincer abnormality does not necessarily lead to OA. However, pistol-grip morphology or a deep acetabulum are present in a significant number of OA cases (Gosvig et al., 2010). In cases of pistol-grip morphology presence of acetabular retroversion will heighten the risk of progression to OA and is a risk factor in its own right (Bardakos and Villar, 2009; Hartofilakidis et al., 2011). Consequently, there is an interactive effect between femoral and acetabular morphology (Neumann et al., 2009).
- There has been found to be significant gender differences with regard to bony abnormality, particularly on the femoral side. It is clear that cam-type morphology is more common in males than it is in females (Gosvig et al., 2007; Jung et al., 2011; Laborie et al., 2011). However, on the acetabular side the findings are less clear, with many studies finding an equal distribution of pincer-type morphologies in males and females (Gosvig et al., 2010; Laborie et al., 2011). This disagrees with the clinical presentation of pincer FAI being predominant in females (Clohisy et al., 2009; Tannast et al., 2007a). However, both Buller et al. (2012) and Laborie et al. (2011) found that females were more likely to show clinical signs of acetabular retroversion. Consequently, separating out the pincer morphologies, acetabular retroversion is more predominant in females while a deep acetabulum is equally likely to be seen in males and females.
- A number of radiological diagnoses have characterised distinct acetabular morphology which differentiates cam and pincer morphologies (Cobb et al., 2010; Laborie et al., 2011; Pfirrmann et al., 2006). Both Cobb et al. (2010) and Pfirrmann et al. (2006) only assessed pure cam and pincer cases and distinguished pincer hips as being deeper than cam hips, rather than classifying retroversion as being distinct within these groups. Consequently, these studies have analysed only pure pathologies, missing mixed cases which many studies still identify as being predominant (Neumann et al., 2009; Philippon et al., 2012; Siebenrock et al., 2004) as well as gender differences (Gosvig et al., 2010; Laborie et al., 2011).

- There has been shown to be a high correlation between bony abnormality and damage to the labrum and articular cartilage (Wyss et al., 2007). Damage location in the anterosuperior region of the acetabulum matches with location of maximum α angle which is also found in this quadrant (Beck et al., 2005; Pfirrmann et al., 2006). Also, pincer type morphology has been found to cause damage to the anterosuperior region but also distinctly to the posterior and posteroinferior regions (Beck et al., 2005; Pfirrmann et al., 2006). Further, MRA analysis has shown that cam morphology is more destructive than pincer morphology.
- The α angle has been shown vary between the 12 o'clock (superior) and 3 o'clock (anterior) regions. The maximum α angle is in the anterosuperior quadrant (Dudda et al., 2009; Rakhra et al., 2009). However, many studies have applied the α angle cut off 55^o defined by Notzli et al. (2002) for the anterior aspect of the femoral head neck junction to identify pathology in the anterosuperior quadrant. The α angle in this region which is symptomatic of cam-type FAI remains undefined. Also, this value is dependent on acetabular morphology to determine whether impingement free motion is possible.
- The shape of the acetabulum has been found to be consistent (Köhnlein et al., 2009). However, it has been found that variation in pelvic tilt, femoral version, acetabular tilt and acetabular inclination may also cause impingement in the normal range of motion as well as variation in bony morphology. Consequently, impingement and joint degeneration is dependent upon a number of interactive factors which include bone morphology (deep acetabulum, femoral hump malformation), hip alignment (pelvic tilt, acetabular version, acetabular inclination, acetabular tilt, femoral version, femoral neck-shaft angle) and activity.

The role of activity has been discussed by a number of studies as being significant in joint degeneration. As well as radiographic studies there have been a number of studies which have assessed FAI dynamically. These will be discussed in the following section.

5 Dynamic assessment

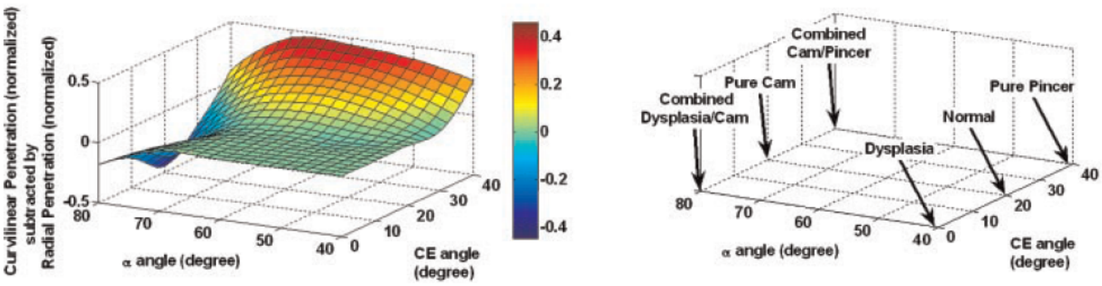
As well as surgical and radiographic analysis of FAI there has been recognition that FAI is a dynamic process and a number of studies have focussed upon different parts of the movement process. These different aspects of motion can be categorised into development of hip joint motion models, three-dimensional range of motion simulation and subject range of motion studies. This section will consider these different research areas.

5.1 Modelling the hip joint

The modelling of the hip joint has traditionally been an intense area of research and recently this has expanded to include movement of FAI patients. There have been a number of methods that have developed which model cam and pincer impingement.

- **Simple method** - Hip joint is modelled with a single rotation centre and all types of impingement are recorded, including inter-articular impingement (Puls et al., 2010).
- **Constrained method** - Hip joint is modelled with a single rotation centre but only collisions within 5mm of the acetabular rim are regarded as impingement (Puls et al., 2010).
- **Translated method** - Hip joint is translated according to a displacement vector which is dependent upon the femoral and acetabular contact, this additional translation is performed for each step of the motion (Puls et al., 2010).
- **Equidistant method** - Determines an equidistant joint space between the femur and the acetabulum in every motion step and translates the hip joint centre accordingly (Puls et al., 2010).
- **Radial penetration depth method** - The degree of impingement or penetration depth between the proximal femur and acetabular rim is modelled along a radial trajectory (Arbabi et al., 2010). Penetration is calculated from a fixed reference, in this case the hip joint centre and is considered suitable in cases where the femoral neck abuts against the labrum, for example in pincer FAI (Arbabi et al., 2009).
- **Circular penetration depth method** - The degree of impingement is modelled along a circular trajectory (Arbabi et al., 2010). Penetration is calculated along a circular arc which is dependent upon the axis of rotation for a motion. It is considered suitable in cases where there is a sliding joint centre, for example in cam FAI (Arbabi et al., 2009).

Arbabi et al. (2010) produced 25 separate models of cam and pincer morphologies with varying centre edge and α angles. Motion data for the sit to stand manoeuvre was modelled



(a) **(b)**

Figure 5.1: Penetration depths of different combinations of centre edge and α angles.

to measure the von mises stresses and penetration depth for the separate models. It was found that hips with cam, pincer and mixed pathologies all experienced penetration prior to finishing the full movement. The maximum circular penetration depth was found for mixed FAI and for maximum radial penetration with cam FAI. The maximum penetration depth and maximum von mises stresses did not occur in the same zone although a cause and effect relationship existed between them. Figure 5.1 shows the normalised penetration depth and how different α and centre edge angles combine to reveal distinct types of FAI morphology.

Puls et al. (2010) assessed four methods of simulating joint motion - simple method, constrained method, translated method and the equidistant method. Three-dimensional CT models of 5 (10 hips) sawbones models and 3 (6 hips) cadeveric samples were used to assess these different motion algorithms. As well as these models the sawbones models and cadeveric samples were also tracked using a surgical navigation system to record the amount of flexion/extension, abduction/adduction and internal/external rotation until collision. This was compared with computer simulation using the three-dimensional models with each of the dynamic motion algorithms. It was found that the equidistant method required less extra motion until collision in comparison to the tracked physical manipulation of the joint than the other dynamic methods. The simple method computed a significantly larger impingement area, and did not reflect the motion behaviour in-vivo as it calculated inter-articular impingement. Translation of the joint centre prevents the calculation of inter-articular impingement. The equidistant method computed the smallest impingement area and showed the highest sensitivity for detection of impingement as well as being the most specific. In conclusion, Puls et al. (2010) commented that the determination of the hip joint centre is crucial for accurate simulation of hip joint range of motion and the precise detection of collision. Further the equidistant method, allowing for a translated joint centre incorporates the findings of Gilles et al. (2009) who were able to show that the hip joint does not move around a fixed centre.

Audenaert et al. (2011) used three-dimensional sawbones models to characterise the shape of the cam lesion and its position in the range of motion. In non-dysplastic hips the femoral head can be approximated to a sphere (Audenaert et al., 2011). Consequently, Audenaert et al. (2011) constructed a sphere from the femoral head surface. Comparing the two surfaces, the femoral head neck junction was evaluated and any points protruding from the surface of the sphere were classified as cam-lesions. Cam resection was calculated by calculating the minimum distance between the fitted femoral head and neck. To simulate range of motion, joint translation was allowed by calculating the normal vector to the femoral and acetabular colliding vertices. Maximum joint translation was constrained not to exceed the average joint space. Range of motion was defined as the point where this translation limit was reached. This allowed evaluation of both the impingement area and contre-coup lesion. Once the the size and location of the cam lesion was defined, the presence of a pincer type lesion was evaluated. This was done by simulating adduction and internal rotation at 90^o flexion using the reshaped proximal femur with the cam lesion removed. The extent of the pincer lesion was determined as the acetabular area penetrated during this motion. This simulation method was found to have diagnostic agreement of 0.96 (95% CI 0.94-0.97) with the α angle measurement calculated for the simulated sawbones models used in the study. Audenaert et al. (2011) states that this method allows the localisation and extent of femoral reshaping to be determined as well as post-operative evaluation of accuracy of the resection, a notable improvement with regard to prototype navigation systems (Brunner et al., 2009).

5.2 Range of motion simulation

Both Kubiak-Langer et al. (2007) and Tannast et al. (2007b) assessed the osseous range of motion of both normal subjects and FAI patients using CT scans. Kubiak-Langer et al. (2007) analysed the range of motion of 33 normal hips (20 male, 13 female) and 28 (24 male, 4 female) hips with anterior FAI, within the FAI group there were 10 cam, 8 pincer and 10 mixed cases. Tannast et al. (2007b) analysed 36 eligible control subjects and 31 hips in the FAI group, within the FAI group there were 12 cam, 7 pincer and 12 mixed cases. These results are shown in Table 5.1, where it was found that in both studies hips with FAI had decreased flexion, abduction and internal rotation with 90^o flexion in comparison to normal hips. Further the location of impingement matched the location of labral and chrondral lesions in anterior FAI. Tannast et al. (2007b) also analysed the impingement subgroups and found that pincer and mixed hips had significantly reduced extension and external rotation with 90^o flexion in compared to cam hips. Pure cam and pure pincer had significantly reduced abduction compared to the mixed pathology. Kubiak-Langer et al. (2007) performed virtual surgery on the FAI patients and re-run the

	Kubiak-Langer et al. (2007)		**Tannast et al. (2007b)**	
	FAI hips	Control hips	FAI hips	Control hips
Flexion	105.2^o (69^o-142^o)	122^o (103^o-145^o)	105^o (σ=16.1^o)	121^o (σ=11.8^o)
Extension	61.1^o (15^o-129^o)	56.5^o (12^o-101^o)	60^o (σ=31.6^o)	58^o (σ=20.4^o)
Abduction	51.7^o (13^o-71^o)	63.3^o (40^o-85^o)	51.9^o (σ=12.1^o)	63^o (σ=11.1^o)
Adduction	34.6^o (17^o-64^o)	32.7^o (4^o-52^o)	34^o (σ=12.6^o)	33^o (σ=11.9^o)
Internal rotation (90^o flexion)	11.1^o (0^o-29^o)	35.2^o (11^o-61^o)	11.7^o (σ=7.1^o)	35^o (σ=12^o)
External rotation (90^o flexion)	83^o (1^o-126^o)	102.5^o (75^o-131^o)	83.1^o (σ=33.1^o)	101^o (σ=14.7^o)

Table 5.1: Analysis of computer simulated osseous range of motion.

range of motion simulation. Virtual resection led to a significant improvement in flexion, abduction and internal rotation with 90^o flexion. Both Kubiak-Langer et al. (2007) and Tannast et al. (2007b) noted a number of limitations with their studies. These included recognition that their simulations were not applicable to the modelling of dysplastic hips with a shallow acetabulum as an unambiguous centre of rotation cannot be found. Also, in cases of advanced OA joint space narrowing leads to a change in the femoral head relative to the acetabulum which results in a non-concentric morphology making joint translation possible. However, in the case of anterior FAI the relevant motions of flexion and internal rotation are limited by bony contact and in cases of advanced OA, surgery to correct bony morphology is not advised. Therefore, in cases of minor OA for important joint motions the modelling approach is justified. Finally, Tannast et al. (2007b) found that range of motion via simulation over-estimated range of motion in normal cases when compared to cadaveric assessment by 5^o as it does not account for soft-tissue tension

Tannast et al. (2008) then went on to correlate their range of motion simulation with inspection of intra-operative labral and articular cartilage degeneration. Two group were recruited, group 1 was the intra-operative group containing 40 (24 cam, 16 pincer) patients in group 2 - the computer simulated group - there were 15 (9 cam, 6 pincer). There was no significant difference between group 1 and group 2 patients and the cam and pincer subgroups with regard to the mean location of labral and cartilage lesions which occurred in the anterosuperior quadrant. The authors did observe a more circumferential pattern of labral and chrondral damage in pincer hips. It was also observed that joint damage observed intra-operatively was larger than the computed impingement area. It was hypothesised that this was because the computer simulation stops as soon as impingement is detected and therefore ignores soft-tissue and deformation of bone under stress. Tannast et al. (2008) stated that the results of the study support existing findings with regard to the association between the presence of labral lesions and the degeneration of the adjacent articular surface. It was also concluded that the maximum hip damage occurs at the impingement impact site between the femoral head-neck junction and the acetabulum and larger damage should be observed intra-operatively in comparison to pre-operative simulation.

5.3 Range of motion studies

There have been a number of recent studies assessing the range of motion in FAI patients and control subjects. Lamontagne et al. (2009) conducted their motion analysis study based on the findings that activities which require a large amount of hip flexion cause the anterosuperior femoral head to roll into the acetabulum. However, for cam-FAI patients the hump-malformation is forced into the acetabulum causing 'outside-in' abrasion of the acetabular cartilage and tearing of the labrum in the anterosuperior region. This occurs typically at the limits of hip range of motion with assisted flexion, internal rotation and adduction. The maximal depth squat is a controlled manoeuvre which can replicate many daily activities that have large flexion with combined adduction and internal rotation. The study asked whether FAI affects the three-dimensional motion of the hip and pelvis during maximal depth of squat and if FAI decreases maximal normalised squat depth. In total their were 15 (9 male, 6 female) eligible cam FAI patients and 11 (6 male, 5 female) eligible control subjects without clinical signs of FAI. Three control patients had to be excluded as they had asphericity of the femoral head-neck junction consistent with cam-FAI but experienced no hip pain. The FAI patients had both a decreased sagittal pelvic range of motion ($14.7^o \pm 8.4^o$) and reduced squat depth (41.5% of leg length ± 12.5%) compared to the control subjects - sagittal pelvic range of motion ($24.2^o \pm 6.8^o$), squat depth (32.3% of leg length ± 6.8%). There was no difference in hip motion between the two groups. As Figure 5.2 shows the control subjects had increased pelvic incline during descent and ascent. However, the largest difference between FAI and control subjects was the increased recline at peak squat depth which was within control group. The more the pelvis is reclined, the less acetabular retroversion occurs, which means at maximum squat depth pelvic recline minimises the contact between the acetabular rim and the femoral head-neck junction. Consequently, decreased sagittal pelvic mobility in cam-FAI is an important finding of this study which highlights the multi-factorial nature of this condition and is an area for ongoing research.

Audenaert et al. (2012) assessed the range of motion in FAI and healthy patients. This was done because when original range of motion studies were conducted the condition of FAI was unknown. Further, the radiological studies presented in section 4 have found that cam and pincer morphologies appear frequently in healthy and asymptomatic cohorts. Consequently, symptomatic and asymptomatic FAI subjects could have been included in these studies. The range of motion of 18 (24 hips) cam patients were compared with 12 (24 hips) asymptomatic volunteers and 12 (24 hips) healthy controls. The range of motion

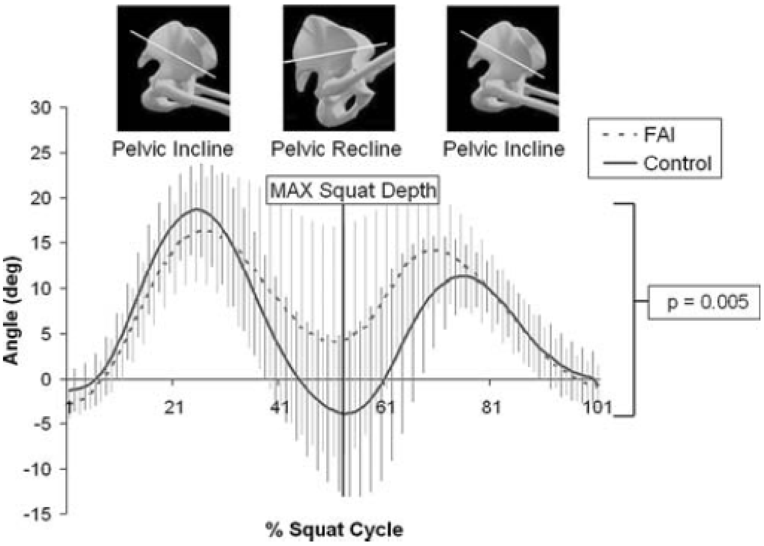


Figure 5.2: Pelvic rotation in the sagittal plane during the maximal depth of squat manoeuvre (Lamontagne et al., 2009).

for these patients is shown in Table 5.2. Comparing the results with the study by (Leunig et al., 2004) who also measured joint motion in FAI patients, Leunig et al. (2004) measured less flexion (101^o) and neutral internal rotation (15^o), internal rotation at 90^o flexion was not measured. Audenaert et al. (2012) found that the kinematics in the asymptomatic group differed at no point from the control, while there were a number of motions that were significantly restricted in the patient group. The significant difference in neutral internal and external rotation was a significant finding because this motion is restricted by soft tissue rather than bony impingement. This suggest that capsular retraction in the presence of pain and synovial irritation might be part of the clinical presentation of FAI. However, the authors did acknowledge that selection bias could have influenced this finding as the majority of FAI subjects were soccer players which commonly present with shortened hip muscles and limited range of motion.

Motion	Patients	Asymptomatic cases	Controls
Flexion	113.7^o (109.7^o-117.7^o)	120.8^o (117.2^o-124.4^o)	125^o (120.6^o-129.4^o)
Neutral internal rotation	28.5^o (25.7^o-31.3^o)	32.5^o (30.1^o-34.9^o)	34.1^o (32.3^o-35.9^o)
Neutral external rotation	28.9^o, (26.8^o-31^o)	38.0^o (34.4^o-41.8^o)	38.4^o (34.6^o-42.2^o)
Internal rotation in 90^o flexion	16.7^o (13.5^o-19.8^o)	27.8^o (25^o-30.6^o)	28^o (24.9^o-31.1^o)

Table 5.2: Measurement of range of motion in the anatomical planes (Audenaert et al., 2012).

5.4 Summary

This section has summarised the findings of recent studies which have attempted to understand FAI as a dynamic process. The key findings of these studies have been summarised.

- Range of motion simulations predicts conflict between the proximal femoral neck and the acetabular rim for both daily activities and pure joint motion. This impingement has been found to occur in the anterosuperior quadrant, the same location as where soft-tissue damage is observed intra-operatively. Although. joint damage is more severe than the impingement models predict.
- Maximum impingement penetration has been found to exist in cases of high centre edge and α angles and addressing both the acetabular and femoral deformity has the maximum improvement upon simulated range of motion, although these simulations do not predict joint stability post-operatively.
- It is unclear whether separate impingement models are required for cam and pincer impingement. Although, having a translated joint centre does allow for modelling of the jamming effect in cam impingement and joint subluxation with prediction of the contre-coup lesion in pincer impingement. A translated or equal joint space method has been found to have good agreement with osseous cadeveric motion experiments with regard to where in the movement cycle impingement occurs.
- The motions of flexion, abduction and internal rotation (neutral and in 90^o flexion) are restricted by FAI and this has been observed both in measurement of FAI patients as well as in range of motion simulations. Virtual bone reshaping has been found to significantly improve range of motion for these restricted motions indicating that correction of the bone abnormality improves a patient's ability to perform their activities of daily living. However, there has been found to be a motion restriction difference between cam and pincer FAI and this is a source for further investigation.
- Range of motion studies have found that there is a significant difference in pelvic motion between cam and normal hips. This pelvic motion is not modelled by recent simulation studies. These findings agree with the skeletal studies of Köhnlein et al. (2009) who hypothesised that factors such as pelvic tilt and acetabular tilt are important factors in the study of FAI as these factors dictate the location of the bony acetabular rim prominences during motion.
- It is unclear how much joint translation occurs after impingement between the proximal femoral neck and acetabular rim. Therefore, in range of motion simulation it is not possible to predict the penetration depth after impingement and so define the

extent of the bone morphology to be corrected. This is due to FAI patients having a significantly reduced range of motion. Consequently, the motion of these patients are required to be measured and simulated with their individual bony morphology to be able to define the penetration depth between the femur and acetabular rim and thus define the amount of bone to be resected.

- Asymptomatic patients with FAI morphology have been found not to have a restriction in their range of motion in comparison to control subjects, unlike symptomatic FAI patients. This is a source for further investigation.

6 Conclusion

This study has reviewed the clinical presentation, diagnosis and research with regard to FAI. Significant findings have included confirmation that there are significant gender differences in FAI morphology as well as a strong correlation between the clinical diagnosis of FAI using the impingement test and the motion simulations which compute the zone of impingement and the soft-tissue damage observed intra-operatively. However, it has been shown that FAI morphology is common within the normal population and presence of this morphology alone does not necessarily mean that subjects will experience motion restriction or joint degeneration. Consequently, the type and intensity of activity a person undertakes has been hypothesised to cause joint degeneration in conjunction with presence of more than one radiological indication of FAI. This means there is a complex interactive effect between morphology and activity. Further, the analysis of the activities that a person with FAI undertakes must consider the motion of the pelvis with respect to the who body as well as the relative alignment of the femur and pelvis in the neutral posture. These factors along with the bone morphology dictate whether impingement will occur as well as its overall severity. This should be the basis of further development with regard to the motion analysis and simulation of FAI patients to obtain a more accurate diagnosis which the surgeon can respond to, to have a more effective surgical plan.

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