Assessing young adults with hip pain can be challenging for the clinician. Although various features from a patient's history and physical examination can be helpful in reaching the correct diagnosis, no particular component of either is entirely diagnostic.¹

A vast differential diagnosis of conditions may cause hip pain, and the symptomatic patient has often been assessed by several practitioners with different perspectives.² With regard to the clinical assessment, the multitude of physical examination maneuvers have varying levels of sensitivity and specificity, thereby limiting their predictive value. In addition, there is a general lack of consistency when executing physical examination maneuvers used to assess the symptomatic hip.³

Subsequently, confirmatory imaging is considered an essential piece to completing the diagnosis and consolidating treatment plans.⁴ An accurate diagnosis ensures that both the clinician and patient can pursue the optimal treatment strategy. The modalities for imaging the hip include a spectrum of testing procedures that provide detail including but not limited to the bony and soft tissue anatomy of the hip and the surrounding periarticular structures. The combination of plain radiographs (XR), magnetic resonance imaging (MRI), and computed tomography (CT) can be helpful when
determining the etiology of hip pain. Further, these modalities can be used individually or collectively to obtain a comprehensive assessment of the hip joint. The use of these modalities requires accurate technique, proper positioning of the patient, and, most importantly, a precise interpretation of results. Their consistent use with standardized and reproducible thresholds further enhances patient care and the ability to conduct academic investigations and research. It is this combination of features of the patient’s history, clinical findings on examination, and imaging findings that will allow a comprehensive assessment of the patient with a symptomatic hip.

This article provides radiologists, clinicians, and researchers with a thorough and comprehensive approach to hip imaging with a focus on imaging strategies to help guide the clinical diagnosis. Using evidence from current literature and knowledge from experienced clinicians, some of the imaging challenges that clinicians face when evaluating the hip are deciphered.

**Techniques**

Presently, XR and MRI are the standard imaging modalities used for diagnosing hip impingement/instability, planning treatment, and outcome assessment. Adequate preoperative characterization and assessment of the osseous morphology is of paramount importance to ensure optimal surgical outcomes for such populations. As an initial diagnostic clinical approach, anteroposterior (AP) pelvis and lateral hip radiographs have traditionally been used and will continue to be (/Fig. 1/).

Nonetheless, relying on XR for the characterization of complex hip pathomorphologies, such as in femoroacetabular impingement (FAI), faces considerable constraints mainly related to inconsistencies in techniques, positioning, imaging quality, and reliability of reports.

With regard to femoral morphology, some authors have demonstrated that the use of a three-view series (AP pelvis, Dunn 45-degree view, and frog-lateral radiographs), a two-view series (Meyer lateral and Dunn 90-degree views), or even a one-view series (Dunn 45-degree view) is adequately sensitive for the evaluation of a cam deformity. In fact, the two-view series just described was reported to provide the most effective predictions of the three-dimensional (3D) shape of the proximal femur. Conceptually, given that the hip is a 3D anatomical structure, fundamental radiologic parameters currently used to diagnose prearthritic hip conditions (i.e., two-dimensional [2D] parameters) would be increasingly facilitated with MRI and CT volumetric imaging (i.e., assessing both 2D and 3D parameters).

Accordingly, 3D assessment of hip morphology has gained increasing attention because it is considered the gold standard for detecting hip deformities. Detection of cam-type FAI on 3D imaging studies (CT or MRI) with radial oblique reformat/acquisitions spanning the anterosuperior neck has gradually been established as the gold standard for morphological assessment. In addition, joint modeling, based on a 3D data set, is used to simulate the effect of osseous morphologies of the hip on joint range of motion, allowing the performance of a virtual impingement analysis. Currently, however, the clinical applicability of these models for routine FAI diagnostics has not been validated.

**Radiographic Techniques and Projections**

XR studies play a critical role in the evaluation and detection of early hip structural disorders, such as developmental dysplasia of the hip (DDH), FAI, and osteoarthritis (OA). These studies may provide the correct information, as long as they are acquired with a reliable standard technique.

Different techniques are described for the axial/lateral view of the hip and also for the AP view of the hip/pelvis that are performed to answer specific questions (online Supplementary Table 1). These views allow assessment of joint congruency and both femoral (head sphericity, head-neck offset, and torsion) and acetabular morphology (coverage, orientation, and depth).

**Anteroposterior Pelvis**

For the pelvis AP radiograph, the legs must be internally rotated 15 degrees to compensate for femoral antetorsion. The central beam is centered to the midpoint between the upper border of the symphysis and a line connecting the two anterior superior iliac spines (/Fig. 2a, b/).

Other technical aspects are paramount to acknowledge including the following:

1. **Conical projection**. XR is based on a point-shaped X-ray source with conical projection. Therefore, distortion of the pelvic anatomy is unavoidable (the closer an object is
located to the beam source, the more lateral it will be projected).

2. **Film–tube distance**: This affects hip anatomy on the XR. For example, by increasing film–tube distance, the apparent acetabular anteversion increases (film–tube distance should be ~120 cm).

3. **Centering and direction of the X-ray beam**: Centering is one of the most important factors influencing pelvic anatomy. To avoid distortion, the craniocaudal angle of the beam is standardized so the sacrococcygeal joint is 1 to 3 cm from the superior aspect of the pubic symphysis. This ensures adequate representation of the acetabulum (by lowering the center of the beam or by moving it to the center of the hip, the apparent acetabular anteversion increases).

4. **Pelvic orientation**: Orientation can vary in three dimensions: obliquity, rotation, and tilt. Although variations in obliquity and rotation can be decreased by a standardized acquisition technique, pelvic tilt can vary substantially. Pelvic tilt mainly affects the apparent anteversion of the acetabulum (with increasing pelvic tilt, the apparent acetabular anteversion decreases).

Proper positioning on an AP pelvic radiograph is recognized when (1) the greater trochanter is seen laterally, and the lesser trochanter is partially superimposed on the femoral neck, (2) the obturator rings and acetabular tear drops are symmetrical, and (3) the midsacral line aligns with the pubic symphysis.

**Supine versus Weightbearing AP Pelvic Radiograph**

XR performed in the supine position is preferred by some authors because the necessary image quality can be secured. Additionally, they can be directly compared with XR performed intraoperatively or at follow-up during early rehabilitation and restricted weightbearing. Conversely, weightbearing radiographs reflect functional anatomical positioning and are recommended by some orthopaedic surgeons as radiographic signs of the acetabular version/coverage vary between the supine and standing positions. In clinical entities where acetabular evaluation is of paramount importance (such as pincer FAI and DDH), weightbearing radiographs should be obtained, given that they account for the differences in pelvic flexion-extension. However, these signs are common on standing radiographs of normal individuals and less reliable compared with measurements on CT and MRI.

Additional functional views may occasionally be necessary. For instance, abduction views are helpful to differentiate between subluxation and true joint space narrowing in DDH.

**Lateral Views**

The most studied and reliable lateral views of the hip include the frog-leg, Lauenstein, cross-table, Ducroquet, Lequesne, and Dunn views (that can be performed with different approaches, namely, Dunn 45 degrees, modified Dunn 45 degrees, or Dunn 90 degrees). These views mainly assess femoral morphology and femoral anterior coverage (Figs. 2–4).

Femoral head-neck (FHN) asphericity is most often localized in the anterosuperior region. Although not consensual, these asphericities are usually best shown with a Dunn 45-degree view because it is thought to be at least equal to other lateral views in the initial evaluation of cam morphology. Using this lateral view as the radiographic standard for the evaluation of FAI provides clinicians with the highest probability of demonstrating a cam morphology (Fig. 3a, b).
The Dunn-Rippstein view (Dunn 90 degrees) (Fig. 3c, d) was originally introduced to measure femoral antetorsion; however, compared with CT- or MRI-based measurements, it is much less accurate and susceptible to patient malpositioning. This projection can be used as an alternative to the axial cross-table view to evaluate the anterior and posterior contour of the FHN junction.

With respect to combinations of lateral radiographic projections, some authors have demonstrated that the use of a three-view or two-view series provides the best approach for the evaluation of a cam morphology. However, it is notable that the $\alpha$ angle and head-neck offset measurements from these and other XR views were reported to describe no more than 50% of the overall variation of the proximal femur shape. In addition, less radiation exposure and affordable care have to be taken into account. Further research should validate current evidence supporting that the Dunn 45-degree lateral view is superior to all other lateral views in the initial demonstration of a cam morphology. Currently, it can be regarded as the first-line diagnostic radiographic imaging for this purpose.

Key Points
1. FHN asphericity is most often localized in the anterosuperior region.
2. Hip morphology is initially best assessed with an AP pelvis radiograph and a Dunn 45-degree view.

MRI Protocol for the Young Hip Patient
Presently, arthrographic and nonarthrographic MRI with radial sequences and version measurement are the
established gold standards for the advanced imaging work-up of young patients with hip pain, particularly if a detailed and thorough protocol is used (►Fig. 5). Until now, there were clear limitations in the ability of MRI to evaluate tridimensional bone morphology, although its value in assessing periarticular soft tissues and intra-articular damage has remained undisputed.

Despite inherently greater radiation doses, CT provides the advantages of 3D assessment for preoperative planning, version analysis, and assessment of global coverage while facilitating postacquisition correction of positioning errors. Although its value in relation to hip pain has not been adequately studied, CT is traditionally considered the best imaging modality for the assessment of bony morphology. This imaging technique involves inherent higher costs (compared with XR) and increased radiation exposure. The total average effective dose of an AP pelvis radiograph and a Dunn lateral view is 1.2 mSv (range: 0.4–2.4 mSv), whereas that of a pelvis CT scan is currently 6.0 mSv (range: 3.3–10.0 mSv). Recently, advanced CT protocols were developed to decrease this exposure by at least a factor of 2 to 3. Because advanced imaging continues to be used for the assessment of FAI and DDH, careful consideration of cumulative radiation exposure is imperative.

MRI with 3D reformats has shown promise and proved to be effective in evaluating shoulder anatomy and instability. Transposing this application to the hip with similar reliability would clearly obviate the need for CT. Evidence was recently uncovered showing that 3D MRI can be used to accurately diagnose and quantify FAI typical osseous pathologic...
conditions, thus eliminating the need for 3D CT.\textsuperscript{39,40} The use of MRI was reported to spare each patient an average radiation effective dose of 3.09 mSv.\textsuperscript{39}

Standard MRI bone modeling is not currently practiced or widely used due to factors such as cost and unavailable automatic segmentation software. Research aimed at developing the necessary protocol to integrate advanced modeling (e.g., statistical shape modeling) into clinical practice is valuable because it could aid in assessing young pre-arthritic patients.\textsuperscript{41} With regard to clinical outcomes, future research is needed to determine if adding advanced 3D hip imaging for presurgical planning would, in fact, improve therapeutical outcomes for young patients.

**Key Point**

MRI with a radial sequence/reformat and femoral antetorsion assessment should be viewed as the minimum ideal protocol to assess hip morphology in the young adult with hip pain.

**Moving from Plain Radiography to CT and MRI**

**Parameters**

**General Considerations**

Regardless of the imaging method used to study the hip, multiple parameters, initially described for XR, have been used indiscriminately to measure osseous morphology with other imaging techniques. When new imaging modalities are utilized, their performances must be assessed before they can be used in clinical practice.\textsuperscript{42,43}

Interchangeability of imaging methodologies to address quantitative measurements has not been widely tested for most 2D hip parameters. In clinical practice, an interchangeability has often been assumed between acetabular and femoral parameters on XR and 2D CT/MRI. This is particularly important when assessing the acetabular component because acetabular orientation, version, and coverage are susceptible to a multitude of positional variations in all planes.

**Limitations**

Accordingly, precise methodology addressing how to measure these parameters is also missing. Unfortunately, no standardized protocols for CT or MRI currently exist that can account for major limitations when using these modalities, namely:

1. **Coronal plane alignment** for measurement of the acetabular lateral coverage (center-edge angle [CEA] and acetabular inclination). Traditionally, an underlying assumption was that a coronal plane (orthogonal to the axial plane passing through the center of the femoral heads at their greatest diameters on axial reference images) coincides with the lateral acetabular rim and represents lateral acetabular coverage. However, multiple factors can influence pelvic position and its inherent relation with the femoral heads, rendering this assumption invalid.\textsuperscript{44}

2. **Slice selection** on coronal 2D imaging (MRI) could influence the measurement of acetabular coverage.\textsuperscript{42}

3. **Pelvic malpositioning and lumbar factors** such as lumbar lordosis/kyphosis and associated pelvic tilt abnormalities
may be associated with apparent overcoverage or undercoverage.  
4. **Precise identification of bony landmarks** has always been somewhat problematic in younger children, where the radiolucent acetabular growth cartilage forms much of the acetabular rim.  
5. **Other anatomical factors** need consideration such as secondary morphological changes in the labrum, ill-defined margins of the acetabular rim, and femoral head asphericity.

It is unclear at present how these secondary abnormalities should be accounted for when standardizing MRI and CT evaluation of the pelvis. These findings highlight the urgent need to develop a standardized technique for the measurement of hip parameters that subtracts potential variations in pelvic tilt abnormality and 3D hip morphology.

**Plain Radiographs and CT**

Scarce literature has specifically addressed the interchangeability of hip parameters between XR and CT. Similar angle measurements were reported by some authors between these modalities, with CT measurements correlating well with some radiographic parameters, namely, acetabular inclination, lateral center-edge angle (L-CEA), and α angles (intermodality reliability, as well as intra- and interrater reliability, of both modalities showed excellent performance) However, this was only achievable if a standardized procedure was used.

These results complement other studies showing consistencies associated with CT-facilitated assessments of the pre-arthritic hip. However, other authors found that measurement of the Wiberg center-edge angle (W-CEA) consistently increased on CT in accordance with clinical etiology (W-CEA was larger by a mean of 4.9–5.1 degrees on CT in hips with DDH), emphasizing the need for standardization and validation of CT-based measurements.

**Plain Radiographs and MRI**

Scarce literature has specifically addressed interchangeability of hip parameters between XR and MRI. Currently, it is largely unknown whether standard morphometric parameters of the hip measured on MRI are comparable with radiographs. Stelzeneder et al showed that MRI provides similar morphometric measurements to radiography for most hip parameters (namely, W-CEA, acetabular inclination, and extrusion index) but not for the anterior center-edge angle (A-CEA). With regard to W-CEA, the estimated differences were within or below the range of previously reported radiographic interrater differences for this parameter, suggesting that MRI can be used to measure a radiograph-like W-CEA angle with sufficient precision. Interestingly, the off-center slice (i.e., 10 mm anterior to the center of the femoral heads) was shown to be the most accurate compared with radiographic W-CEA.

However, considering all parameters, it is unclear why there is less agreement (or with conflicting results) between MRI (and also CT) concerning L-CEA and femoral neck shaft angles compared with other assessments of osseous morphology.

**Standardization Protocol**

Despite all efforts to standardize patient positioning before image acquisition, some degree of pelvic rotation and tilting is frequent. To standardize pelvic malpositioning, 3D pelvic images should be processed via image manipulation to correct for pelvic tilt and rotations. However, it can be argued that pelvic orientation after correction might not represent the patient’s functional alignment. However, it certainly allows for accurate and reproducible measurements as previously reported and is currently used in multiple centers.

Newer methods for the measurement of hip morphology, ideally involving the determination of 3D measurements with 3D MRI and low-dose 3D CT, may be warranted to improve the quality of diagnostic preoperative imaging and subsequent clinical decision making.

**Key Points**

1. Hip measurements interchangeability between XR, CT, and MRI should be done with great caution and following a strict standardized protocol.
2. A radiation-free 3D MRI protocol can facilitate such measurements.

**Radiologic Signs and Parameters (XR and Cross-Sectional)**

**What They Are and How to Measure Them**

Overall, the most commonly described parameters to assess acetabular morphology can be divided according to the main features that they measure, that is to say, depth, coverage, and orientation (**Fig. 7** and **Table 1**).

Similarly, the most commonly described parameters to assess femoral morphology can be divided according to the main features that they measure, namely joint congruency, femoral head sphericity, and other important parameters such as neck orientation in the coronal (neck-shaft angle) and in the axial (torsion) planes (**Fig. 8** and **Table 2**).

**Thresholds: A Scoping Review**

Thresholds of hip quantitative parameters have been extensively debated, mainly due, on one hand, to a lack of agreement regarding which imaging method should be used to establish such thresholds or, on the other hand, due to the lack of consensus regarding what kind of reference interval is ideal in the setting of hip-preserving surgery.

Reference intervals (RefInt) are the most widely used tools for the interpretation of hip quantitative measurements. These involve obtaining samples from a healthy population and then...
Fig. 6 Steps to use volumetric imaging and obtain comparable computed tomography and magnetic resonance imaging measurements between examinations and for research purposes. (1) Correction of tilt on the coronal plane: aligning the superior edges of the femoral heads or the inferior margins of the ischial tuberosities. (2) Correction of rotation in the axial plane: aligning both posterior acetabular wall margins or the anterosuperior iliac spines (ASIS). (3) Defining the anterior pelvic plane (APP) (correction for tilt in the sagittal plane): aligning the ASIS and the anterior edge of the pubic symphysis. The APP is thus defined by three bony landmarks, the ASIS on both sides and the pubic symphysis. The angle between the APP and the horizontal is defined as the APP angle. Perpendicular to the APP, multiple planes can be generated covering both acetabula from top to bottom. On each of these planes, the acetabular version can be determined, usually measured at the center of the femoral head (central acetabular version; Anda et al, 1986) or 5 mm from the acetabular roof (cranial acetabular version; Jamali et al, 2007). (4) Femoral measurements: The center of the femoral head is identified by placing a circle over the contour of the femoral head. The femoral neck axis (FNA) can be defined as a line that passes through the center of the femoral head and the center of the femoral neck at its narrowest point, although other anatomical methods may be applied (Bouma et al, 2014). For measurements of the proximal femur with neutralization of the femoral torsion, a reconstruction in the coronal plane of each hip is performed. The femoral coronal plane is defined as the plane between the FNA in the axial reconstruction and the long axis of the femur in the sagittal reconstruction. (5) Radial reformats performed along the FNA at 15- to 30-degree intervals allows obtaining images for the alpha angle/offset measurement; 12 o’clock indicates the femoral superior (lateral) location (identified as corresponding to the most prominent image of the great trochanter), and 3 o’clock indicates the anterior location according to the mapping system suggested by Klenke et al (2015).
identifying the outermost 5% of cases to define interval limits. More recently, decision limits, commonly called “cutoff values,” based on outcome analysis were also introduced to aid in test interpretation. However, the distinction between RefInt limits and decision limits has become blurred.

RefInt can be viewed in multiple ways, namely, (1) the most representative value of a parameter as defined by the mean; (2) the most commonly encountered values of such a parameter as defined by an interval (i.e., the usual 95% RefInt); (3) parameter values associated with a clinical event/outcome; and (4) a committee’s consensus of reference intervals. In radiology and orthopaedics, researchers are usually interested in “normality” in terms of definitions 2 or 3.

Which Population to Study
The reference population must be carefully defined on the basis of the intended clinical use of the underlying test. If a particular characteristic guides the definition of the reference population (e.g., nonsymptomatic and/or individuals with non-OA hips), then this population should reflect a random sampling of such individuals. But if pain and OA is not the underlying concern, but rather the epidemiological relationship of an individual’s hip shape with the population at large, the most appropriate reference population will be made up of randomly selected individuals from the general population. Presently, interpretation of hip shape in combination with clinical information seem to represent a better way to assess the likelihood of determining a patient with FAI/DDH.

Reference intervals (epidemiological use): Defined by threshold values between which the values of a specified percentage (usually 95%) of apparently healthy individuals would fall. The threshold or limiting values for the RefInt are usually the 2.5% and 97.5% fractions of the parameter distribution in the reference population.

Reference intervals (defined by a specific clinical outcome): Whereas the 97.5 percentile (upper limit) for, for example, the \( \alpha \) values in the general population lies between 70 and 77 degrees,49,51,52 the upper reference limits for \( \alpha \) as defined by a specific clinical outcome (hip pain) would correspond to 57 to 60 degrees (which in turn corresponds approximately to the 50–75th percentile of the “epidemiological RefInt”). These values were determined having a specific clinical outcome in mind because they were associated with hip pain in specific studies. For FAI assessment, it is reasonable to suggest that defining RefInt based on an asymptomatic healthy reference population may ultimately be the preferred approach.

Reference intervals (based on the genotype and/or phenotype): It is now known that the most commonly encountered values (reference values) for some parameters vary with some factors of the individual (e.g., \( \alpha \) angle variation with sex27 and race27). Several phenotypic/genetic markers are known to have a role in hip shape, and it is possible that yet undefined markers may influence observed RefInt for hip parameters.

Part of the reason that population overlap has been observed in the distributions of quantitative hip parameters in asymptomatic individuals and patients with femoroacetabular impingement syndrome (FAIS) is that determination of hip impingement depends on many variables beyond the tests performed in hip imaging. Examination of any single parameter will not necessarily provide a definitive diagnosis in a given patient. A potential solution to this problem is to develop a multidimensional reference region or multivariate approaches. In fact, when quantitative parameter results for both asymptomatic and individuals with FAIS are
available, various approaches can be used to set decision limits for these parameters by examining the test sensitivity and specificity at various test threshold settings. Such thresholds are best set by the use of receiver operating characteristic (ROC) analysis. Examples of studies that have used this approach for setting decision limits of tests in FAIS include those by Mascarenhas et al.53 and Sutter et al.55 in the hip-preserving surgery field.

Table 1 Imaging parameters to describe acetabular morphology

<table>
<thead>
<tr>
<th>Acetabulum</th>
<th>Parameter</th>
<th>Values</th>
<th>Imaging technique</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>Coxa profunda</td>
<td>Positive/Negative</td>
<td>AP pelvis</td>
<td>AF touches or crosses the IIL</td>
</tr>
<tr>
<td></td>
<td>Protrusio acetabuli</td>
<td>Positive/Negative</td>
<td>AP pelvis</td>
<td>FH touches or crosses the IIL</td>
</tr>
<tr>
<td></td>
<td>Acetabular depth</td>
<td>Positive/Negative</td>
<td>CT/MRI transverse oblique image of the FN long axis</td>
<td>Distance between center of FH and line connecting the anterior/posterior acetabular rim. If ≤ 3 mm, considered positive for pincer morphology (Leunig et al, 2013)</td>
</tr>
<tr>
<td>Coverage</td>
<td>Lateral center-edge, L-CEA</td>
<td>(angle)</td>
<td>AP pelvis CT/MRI</td>
<td>Angle formed by a vertical line (v) and a line through the center of the FH (C) and the lateral bony rim of the acetabulum</td>
</tr>
<tr>
<td>Coverage</td>
<td>Center-edge angle of Wiberg, W-CEA</td>
<td>(angle)</td>
<td>AP pelvis</td>
<td>Lateral end of the sourcil (i.e., the weightbearing area of the acetabulum), rather than the lateral rim of the acetabulum</td>
</tr>
<tr>
<td>Coverage</td>
<td>Acetabular roof angle of Tönnis or acetabular inclination</td>
<td>(angle)</td>
<td>AP pelvis CT/MRI</td>
<td>Angle formed by a horizontal line and a line through the medial and lateral edge of the acetabular roof</td>
</tr>
<tr>
<td>Extrusion index (%)</td>
<td></td>
<td>AP pelvis</td>
<td>% of the FH width not covered by the acetabulum</td>
<td></td>
</tr>
<tr>
<td>Sharp angle (%)</td>
<td></td>
<td>AP pelvis</td>
<td>Angle between a horizontal line (HL) and a line connecting the teardrop (TD) and the lateral bony rim of the acetabulum</td>
<td></td>
</tr>
<tr>
<td>ADR</td>
<td>NA</td>
<td>AP pelvis</td>
<td>The depth of the acetabulum divided by the width of the acetabulum, multiplied by 1,000, presented as a ratio: (A/B) / 1,000</td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td>PW sign</td>
<td>Positive/negative</td>
<td>AP pelvis</td>
<td>Positive if the PW runs medially to the center of FH (C)</td>
</tr>
<tr>
<td></td>
<td>AWI and PWI</td>
<td>Positive/negative</td>
<td>AP pelvis</td>
<td>Ratio of the width of the acetabular AW/PW measured along the FN axis (a) divided by the FH radius (r)</td>
</tr>
<tr>
<td></td>
<td>Crossover sign</td>
<td>Positive/negative</td>
<td>AP pelvis</td>
<td>AW crosses laterally the PW</td>
</tr>
<tr>
<td></td>
<td>Retroversion index (%)</td>
<td>AP pelvis</td>
<td>% of retroverted acetabular opening divided by entire opening</td>
<td></td>
</tr>
<tr>
<td>Ischial spine sign</td>
<td>Positive/negative</td>
<td>AP pelvis</td>
<td>Positive if IS is projected medially to PB</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: AASA, anterior acetabular sector angle; ADR, acetabular depth-width ratio; AF, acetabular fossa; AP, anteroposterior; AW, anterior wall; AWI, anterior wall index; CT, computed tomography; FH, femoral head; FN, femoral neck; IIL, iliolumbar line; IS, ischial spine; L-CEA, lateral center-edge angle; MRI, magnetic resonance imaging; NA, not applicable; PASA, posterior acetabular sector angle; PB, pelvic brim; PW, posterior wall; PWI, posterior wall index; W-CEA, Wiberg center-edge angle.

Figure 7 shows the corresponding illustration.
Key Point

In the setting of hip-preserving surgery, defining reference intervals based on an asymptomatic healthy reference population and defining decision limits based on a clinical outcome may ultimately be the preferred approach.

Acetabular Assessments

What They Are and How to Measure Them

The diagnostic preoperative assessment of the acetabulum is confined to the recognition of the osseous and cartilage under- and overcoverage of the femoral head and acetabular version with correlation to femoral head and neck abnormalities. In addition, imaging should visualize localized under- and overcoverage for dedicated measurements.

AP radiography of the pelvis provides important information concerning acetabular coverage, defined by a line connecting the lateral and medial margins of the acetabular roof/sourcil (respectively, point E and the superior-lateral margin of the acetabular fovea) (Fig. 9a, b). The A-CEA (Fig. 7f) is measured on the oblique false-profi le standing lateral radiograph of the hip. This measurement requires precise and reproducible 65-degree oblique positioning of the pelvis that may be difficult to obtain and assess. There are several other measures of acetabular depth and coverage (Table 2), but these are less commonly used in the general therapeutic decision-making process.

The crossover sign, crossover index, posterior wall sign, and ischial spine sign (Fig. 7g) may serve as indicators of a reduced acetabular version or acetabular retroversion but should not determine therapeutic decisions as isolated findings. Such signs are commonly present on radiographs of normal subjects, although they may be significant if clearly abnormal or several of these signs are present. Some authors consider them to be less reliable compared with CT measurements of the acetabular version.

The most superolateral osseous margin of the acetabulum is commonly used for the measurement (Fig. 9a), resulting in the L-CEA. Surprisingly, the W-CEA is often connected with Ogata et al and the L-CEA with Wiberg. However, Ogata et al suggested the same measurement as described earlier by Wiberg. It is important to distinguish precisely between W-CEA and L-CEA. The W-CEA represents the weightbearing superolateral coverage and the L-CEA expresses the bony acetabular extension laterally.

The acetabular inclination (Ac-inclination), or acetabular index, is a commonly used supplementary measure of acetabular coverage, depicted by a line connecting the lateral and medial margins of the acetabular roof/sourcil (respectively, point E and the superior-lateral margin of the acetabular fovea) (Fig. 9a, b).

The crossover sign, crossover index, posterior wall sign, and ischial spine sign (Fig. 7g) may serve as indicators of a reduced acetabular version or acetabular retroversion but should not determine therapeutic decisions as isolated findings. Such signs are commonly present on radiographs of normal subjects, although they may be significant if clearly abnormal or several of these signs are present. Some authors consider them to be less reliable compared with CT measurements of the acetabular version.
CT and MRI for measuring the amount of acetabular coverage (both craniocaudal and AP) and version should include volumetric data and appropriate software to secure alignment of the centers of the femoral heads in the true coronal and transverse planes (Fig. 10). Measurements are performed with the patient in a supine position and may not represent the functional position of the acetabulum. The anterior pelvic plane (APP) or pelvic tilt can be adjusted to a functional position of the pelvis. In relevant cases, pelvic inclination on a low-dose standing lateral radiograph of the pelvis can also be used for functional alignments.

Landmarks in the transverse plane are the most anterior lateral and posterior osseous margins of the acetabulum. Acetabular version (Ac-version), anterior acetabular sector angle, and posterior acetabular sector angle are measured relative to the coronal plane (Fig. 10b). The landmarks in the coronal plane, superolaterally (12 o’clock), are the osseous and weightbearing margins of the acetabulum, respectively, defined as the L-CEA and W-CEA angles (Fig. 10c). The location of point E on the lateral margin of the acetabular weightbearing zone may be difficult to determine; by CT, it is located where the concave acetabular roof ends laterally or at the lateral margin of the dense subchondral bone. On MRI, the point of the transition between the acetabular cartilage and the labrum was suggested. Measurement of Ac-inclination also relies on point E at 12 o’clock in the coronal plane and the medial edge of the acetabulum medially. The latter landmark is frequently difficult to identify on CT and MRI (Fig. 10, Fig. 11).

Acetabular coverage is additionally determined by the CEA at 11:00 and 01:00 hours (h) or at 1 h or 30-minute intervals from 9 to 3 o’clock by rotation of the data set in the sagittal plane around the axis between the centers of the femoral heads (Fig. 11c). Both the W-CEA and L-CEA should be measured. Center Ac-version can be measured at the center of the femoral heads (more straightforward) or at the center of the acetabulum. Upper Ac-version can be measured either by using the 5-mm reference distance from the acetabular roof according to Jamali et al or by using the line connecting the points of the osseous landmarks/the margins of the acetabulum at 11:00 and 01:00 h. This upper Ac-version measurement corresponds to the upper one fifth of the acetabular radius in the sagittal plane. The points of measurement are well defined compared with direct measurement of upper version on transverse slices that are commonly flawed due to partial volume.

The measures of acetabular coverage can finally be confirmed visually by assessing 3D surface reconstructions.

Thresholds

The epidemiological reference intervals of CEA measurements were assessed in three large population-based studies (epidemiologic RefInt) (-Table 3). The values of the originally described W-CEA measurement according to Wiberg were only reported by Laborie et al. The difference of 2 to 3 degrees between W-CEA and L-CEA was not further analyzed by Laborie et al. However, other studies have emphasized much larger differences, particularly in dysplastic hips. L-CEA < 25 degrees is observed in up to 20% of the population, and 25% may be classified as having dysplastic hips when using cutoff values of 25 degrees for the W-CEA. Therefore, a cutoff of 15 degrees for the W-CEA is suggested most relevant for diagnosing definitely pathologic dysplastic hips, with values of 15 to 20 degrees indicating less severe dysplasia. However, localized deficient coverage, increased Ac-inclination, and abnormal Ac-version may influence these ranges.

In the setting of FAI, both W-CEA and L-CEA should be measured and assessed, and the osseous margins...
corresponding to L-CEA may, in cases of overcoverage, be the most valuable from a preservation treatment perspective.\textsuperscript{51,61} The reference values of W-CEA, L-CEA, and Ac-index with respect to overcoverage appear in Table 4. However, L-CEA RefInt are wide, and values of 23 to 33 degrees were suggested.\textsuperscript{48} All global and localized measures of overcoverage should be assessed in relation to femoral and pelvic parameters.\textsuperscript{53}

**Acetabular Inclination**

The RefInt and cutoff values for Ac-inclination were determined in large population-based cohorts evaluated by XR with mean values of 3.8 to 5.6 degrees (95% RefInt: − 7 to 15 degrees), in large asymptomatic cohorts evaluated by CT\textsuperscript{51} with mean values of 3.4 ± 5.4 degrees (95% RefInt: − 8 to 14 degrees), and by MRI with mean values of 2.9 ± 5.4 degrees (95% RefInt: − 8 to 14 degrees).\textsuperscript{53}

Recently, a decision limit threshold of 6 degrees was suggested (sensitivity 65%, specificity 70%; area under the curve [AUC]: 0.709) to predict a symptomatic hip (with decreasing superior acetabular coverage; i.e., by increasing Ac-inclination, more symptomatic hips were found). In fact, likelihood of symptomatic disease doubled with a 7-degree Ac-inclination increase.\textsuperscript{53}

| Table 2 Imaging parameters to describe femoral morphology\textsuperscript{a} |
|---------------------------------|----------------|-----------------|-----------------|
| **Femur and joint** | **Parameter** | **Unit** | **Imaging technique** | **Definition** |
| --- | --- | --- | --- |
| Femur sphericity | Alpha (beta) angle | (angle) | Axial and AP pelvis CT and MRI | Angle formed by FHN axis and line through center of the femoral head and point where the anterior (posterior) FHN contour exceeds head radius |
| Pistogrip deformity | Qualitative | Axial and AP pelvis | Seen as bump at FHN junction other than osteophytes |
| Flattening of lateral aspect of femoral head | Qualitative | Axial and AP pelvis CT and MRI | Flattening of normal concavity of the FHN junction |
| Asphericity | Qualitative | Axial and AP pelvis | The head is said to be aspherical if femoral epiphysis extended > 2 mm outside the reference circle corresponding to a spherical head |
| Gamma (delta) angle | (angle) | AP pelvis | Angle formed by FHN axis (a) and line through center of the FH (C) and the point where the cranial (caudal) FHN contour exceeds the head radius |
| Offset | [mm] | Axial and AP pelvis CT and MRI | Difference (o) between FH radius (r) and neck radius |
| Offset ratio | NA | Axial and AP pelvis CT and MRI | Ratio of offset (o) to the FH radius (r). |
| Femoral distance | [mm] | Axial and AP pelvis CT and MRI | Perpendicular distance between a tangent along anterior cortex of the FN and point of largest osseous deformity at the FHN junction |
| Triangular index | NA | AP pelvis | Perpendicular line (p) is drawn at half the head radius (r). Distance (R) is measured from the FH center (C) to the point where p intersects the anterior FHN contour. |

**Joint congruency**

| | **Shenton’s line** | **Intact/Interrupted** | **AP pelvis** | Interrupted if the caudal FHN contour and superior border of the obturator foramen do not form a harmonic arc |
| Lateralization of femoral head or position of the hip center | (mm) | AP pelvis | Shortest distance between medial aspect of FH and ilioischial line (IIL). Lateralized if > 10 mm |

**Additional findings**

| | **Cervicodiaphyseal angle** | (angle) | AP pelvis CT/MRI | Angle formed by FHN axis (C) and femoral shaft axis (D) |
| Fovea angle delta | (angle) | AP pelvis | Angle formed by a line through the medial edge of the acetabular roof (M) and the center of the FH (C) and a line through the lateral border of the fovea capitis (F) and (C). An angle ≤ 10 degrees is associated with DDH |

**Joint space width**

| | **Joint space width** | (mm) | AP pelvis standing | Measured at point of narrowest joint space width |

**Femoral torsion**

| | **Femoral torsion** | (angle) | Transverse images over proximal and distal femur (CT, MRI, or Dunn 90 degrees) | Angle between the long axis of the FN and tangent at the condyles of the distal femur |

Abbreviations: AP, anteroposterior; CT, computed tomography; DDH, developmental dysplasia of the hip; FH, femoral head; FHN, femoral head-neck; FN, femoral neck; MRI, magnetic resonance imaging; NA, not applicable.\textsuperscript{a} Figure 8 shows the corresponding illustration.
**Acetabular Version**

The RefInt and cutoff values for center Ac-version (the midaxial slice through the center of the femoral heads) were determined in large asymptomatic cohorts\(^{51,53}\) with mean values of 21 ± 5 degrees (95% RefInt: 12–31 degrees; 4–5 degrees higher in females). Similar findings were seen in other studies using XR\(^{63,77}\), CT\(^{82–84}\), and MRR\(^{53}\).

Landmarks for measuring Ac-version in the upper hemisphere have rarely been defined in the literature, probably because this part of the acetabulum is often purely defined in the horizontal plane, but mild retroversion is common\(^{22,85}\). Differences between the 11:30/01:30 h and 11:00/01:00 h L-CEAs may represent a more appropriate measure of the upper Ac-version, but reference values are not widely available. Jamali et al proposed measuring the cranial acetabulum version at 5 mm from the acetabular roof, which may be regarded as a more practical approach.

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**Fig. 10** Measurements of acetabular parameters on multiplanar computed tomography (CT) reconstructions. The centers (C) of the right and left femoral head are obtained by the best fit of multiple points on the osseous surface of the femoral head in three planes (a, b, and c). The line joining the centers of femoral heads is aligned into the coronal and axial plane. (a) W-CEA at 12:00 h is the angle between line CE and a line perpendicular to line CC. (b) Point A and P is the anterolateral and posterolateral margin of the concave acetabular joint surface in the horizontal plane. The mid-transversal acetabular version (Ac-version) is the anterior angle between line A-P and a line perpendicular to the line CC. The anterior acetabular sector angle (AASA or CEA; 3:00 h) is the medial angle between line A-C and C-C (anterior white line). The posterior acetabular sector angle (PASA or CEA; 9:00 h) is the medial angle between line C-P and C-C (posterior white line). (c) Sagittal slice through the center of the femoral head. (d) CEA measurement in the oblique coronal plane at 1:00 h. The oblique coronal plane is determined by the line CC and CE (11:00 h) as in (a). A similar measurement is performed at 1:00 h (not shown). A line is drawn between point E at 1:00 and 11:00 h to obtain the cranial acetabular version shown as the short green line on (e). There is retroversion superiorly. For comparison the Ac-version at mid-transversal level is displayed as a long green line corresponding to the line shown on (b). A, anterior; C, center of femoral head; E, edge; I, inferior; P, posterior; S, superior.
**Key Points**

1. CEA, Ac-inclination, and Ac-version are the most important parameters to define acetabular morphology.
2. Precise definition of whether the L-CEA or W-CEA is used is paramount.

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**Femoral**

**The α Angle**

**General Considerations**

The quantitative parameter most widely used to evaluate cam-type morphology is the α angle because it represents the degree of asphericity of the FHN junction (Fig. 12). The original method (method 1 of Nötzli et al.) was described in an axial oblique arthro-MRI image and is commonly known as...
Table 3 Reference intervals of acetabular measurements obtained in selected population-based studies and asymptomatic populations

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Study</th>
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<th>N</th>
<th>Modality</th>
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<td>13</td>
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Abbreviations: Ac-inclination, acetabular inclination or index; CR, conventional radiography of the pelvis including both hips; CT, computed tomography; F, female; L-CEA, lateral center-edge angle; M, male; MR, MRI of the pelvis including both hips; W-CEA, weightbearing center-edge angle of Wiberg.

*Population-based-studies.

Asymptomatic cohort.

The “three-point method” (uses one single point to construct the neck axis). Another method known as the “anatomical method” (later described by Bouma et al) uses multiple points to define the femoral neck axis (FNA) and attempts to define the true anatomical axis. Depending on the method used, the α angle may or may not account for other morphological characteristics such as head-neck offset. In both, the α angle measurement requires identification of the FNA.

The main limitations of the α angle are (1) only moderate reproducibility, (2) incomplete quantification of cam morphology, and (3) suboptimal accuracy in distinguishing patients with FAIS from healthy individuals (due to substantial overlap in α angle measurements between these groups). This further emphasizes that the radial analysis of the FHN junction is paramount, and perhaps in conjunction with 3D models, it is able to provide clinicians with another perspective to analyze a femoral deformity.

The most common position in which the largest α angle and raised α angle are found coincides with 1 and 1:30 o’clock on the clock face. In fact, in asymptomatic individuals, the maximum mean α angle is most commonly located anterosuperiorly at 1:14 to 1:36 o’clock. Factors such as race and sex, definitely influence α angle values (higher α angles are expected in males and also in whites compared with Africans and finally Asians). Yanke et al and Mascarenhas et al found that men have larger cam radial extension, higher maximal mean increased α angle, and epicenter superiorly located in the anterosuperior quadrant (1 versus 1:30 o’clock). As such it is important to recognize that the plane of measurement greatly influences the α angle (Fig. 13).

Two systematic reviews reported that the prevalence of an asymptomatic cam morphology ranges from 7% to 100% (mean: 22.4 ± 6.2%). The mean α angle in those asymptomatic hips was, respectively, 47 degrees (±2.0 degrees) and 54.1 degrees (±5.1 degrees) (irrespective of the imaging method or measurement location around the femoral head). In contrast, in asymptomatic cohorts evaluated with 3D CT, a
<table>
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<td>Mascarenhas et al, 2018&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Asymptomatic</td>
<td>590</td>
<td>CT 3D (3:00/1:30)</td>
<td>14–45</td>
<td>46/58</td>
<td>58/70</td>
<td>5.8/6.5</td>
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<tr>
<td>M</td>
<td>271</td>
<td></td>
<td></td>
<td>46/60</td>
<td>57/70</td>
<td>5.9/6.5</td>
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<tr>
<td>F</td>
<td>319</td>
<td></td>
<td></td>
<td>46/56</td>
<td>57/69</td>
<td>5.7/5.9</td>
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<tr>
<td>Mascarenhas et al, 2018&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Asymptomatic</td>
<td>372</td>
<td>MR 3D (3:00/1:30)</td>
<td>33.9 ± 8</td>
<td>46/56.6</td>
<td>37.05/70.5</td>
<td>5.8/7.1</td>
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<td>M</td>
<td>186</td>
<td></td>
<td></td>
<td>17–50</td>
<td>56/73.5</td>
<td>5.7/7.2</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>186</td>
<td></td>
<td></td>
<td>17–50</td>
<td>45.3/54</td>
<td>5.8/6.1</td>
<td></td>
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<tr>
<td>Gollwitzer et al, 2018&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Random</td>
<td>1,312</td>
<td>CT 3D (1:30)</td>
<td>61.2</td>
<td>59</td>
<td>9.4</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: 3D, three-dimensional; CR, conventional radiography of the pelvis, including both hips; CT, computed tomography; F, female; FL, frog-leg lateral; M, male; MR, MRI of the pelvis including both hips; SD, standard deviation.

<sup>a</sup>Population-based studies.

<sup>b</sup>Asymptomatic cohort.
higher prevalence of cam morphology was found, reaching 79% for a 55-degree $\alpha$ angle and 33% for a 60-degree $\alpha$ angle threshold, respectively.\textsuperscript{27,51}

**Key Points**

1. Quantitative 3D morphometric assessment allows a thorough and reproducible hip morphology diagnosis and monitoring.
2. Cam and $\alpha$ angles/thresholds should be defined according to sex and location around the FHN.
3. Cam prevalence, magnitude, location, and epicenter differ significantly by sex.

**Thresholds**

Nötzli et al described the $\alpha$ angle and established that impingement was associated with a value $> 55$ degrees (oblique axial MRI plane). Later on, other authors referenced 50 degrees\textsuperscript{19} (oblique axial MRI plane) and 50.5 degrees\textsuperscript{92} as indicators of a cam morphology. Changes used on imaging views to observe the $\alpha$ angle in different radiographic planes and multiple radial positions\textsuperscript{89,92,93} around the clock face not only improved the assessment of the cam morphology but also provoked more confusion and discussion regarding RefInt.

Multiple studies have used different cutoff values for morphometric parameters of cam-type FAI.\textsuperscript{92,94} Accordingly, more recent studies pointed out the high prevalence of radiographic findings that are suggestive of FAI in asymptomatic populations when applying currently used diagnostic thresholds, emphasizing the need for a reevaluation of these cutoffs.\textsuperscript{84,94}

Recognizing that a cam morphology was statistically prevalent at the anterosuperior FHN, an $\alpha$ angle value $> 60$ degrees in the radial 1:30 plane was suggested as an upper threshold and predictor of hip pain.\textsuperscript{92} Individuals with a higher $\alpha$ angle, thus with a more severe deformity, had prevalent anterosuperior labral and cartilage lesions that were confirmed with open surgical hip dislocation and imaging.\textsuperscript{95,96}

Presently it is acknowledged that RefInt limits are beyond the abnormal thresholds initially reported in the literature.
Revisiting the current $\alpha$ angle intervals used in the diagnosis of cam and FAIS is paramount. Conceptually, increasing the threshold of an abnormal $\alpha$ angle would improve its specificity, prevent overdiagnosis of FAIS, and consequently decrease the number of unnecessary surgeries.\(^\text{93,97}\)

**Reference intervals:** Based on several large asymptomatic cohorts (\(\text{\textbullet \ Table 4}\)), an $\alpha$ angle upper-limit RefInt of 60 degrees for the 12:00/3:00 positions and 65 to 70 degrees for the 1:00/1:30 o’clock positions was proposed.\(^\text{27,51}\)

Although higher than the previously published thresholds of 50 to 55 degrees,\(^\text{86,92}\) these results are in agreement with several recent works, namely, from Agricola et al\(^\text{97}\) (who also measured the $\alpha$ angle at the 12:00 position), which is similar to a recent report using MRI\(^\text{93}\) (that suggested increasing the threshold to 63/66 degrees at 3:00/1:30 o’clock, respectively) and a population-based report\(^\text{52}\) (mean $\alpha$ angle of 59 $\pm$ 4.4 degrees).

**Reference intervals with clinical impact (“decision limits”):** Increasing the threshold of an abnormal $\alpha$ angle, while considering its discriminative ability, will additionally improve its value as a diagnostic test (i.e., introducing a useful “decision limit”). Therefore, we suggest using the threshold of an abnormal $\alpha$ angle in the setting of a diagnostic test to incorporate higher discriminative power. An upper $\alpha$ angle limit of 57 to 60 degrees measured at 1:00/1:30/2:00 o’clock and 50 degrees at 3:00 o’clock would optimize discriminative power while favoring specificity for a FAIS diagnosis.\(^\text{53}\)

**Key Points**

1. The 95% reference interval limits of cam morphotype are beyond, that is, higher, than currently defined thresholds.
2. Epidemiological reference intervals: 95% reference interval $\alpha$ angle upper limit of 60 degrees for the 12:00/3:00 o’clock positions and 65 to 70 degrees for the 1:00/1:30 o’clock positions.
3. Decision limit: An upper $\alpha$ angle limit of 57 to 60 degrees measured at 1:00/1:30/2:00 o’clock and 50 degrees at 3:00 o’clock optimizes discriminative power while favoring specificity for a diagnosis of FAIS.

**Offset and Offset Ratio**

Another way to assess the FHN junction is to measure the offset. Anterior offset is the difference between the anterior femoral neck radius and the anterior femoral head radius, initially described in a cross-table radiographic view although later used in both CT and MRI.\(^\text{84}\) The anterior head-neck offset ratio is defined as the offset divided by the diameter of the femoral head\(^\text{98}\) (\(\text{\textbullet \ Fig. 14}\)).

The offset has been proved to differ in patients versus controls, showing a significant reduction in mean head-neck...
offset on the anterior aspect of the femoral neck in the symptomatic group, consistent with the site of impingement in flexion and internal rotation, and with lesions of the adjacent rim. In asymptomatic hips, an anterior offset of $11.6 \pm 0.7$ mm was considered normal; hips with cam impingement had a decreased anterior offset of $7.2 \pm 0.7$ mm in the initial study conducted by Eijer et al. As a general rule for clinical practice, an anterior offset $< 8$ mm is an indicator for risk of cam impingement. Smaller offset values indicate the presence of a cam-type deformity. An offset ratio $\leq 0.15$ was proposed as representing a risk for impingement, and $\leq 0.17$ was considered pathologic (online Supplementary Table 2).

Interobserver agreement (intraclass correlation coefficient [ICC]) was reported to be good (0.657) for offset, however, with ROC analysis and AUC $< 0.666$. The interclass and intraclass agreement for anterior offset was reported to be good ($> 0.72$).

Anterior Femoral Distance and Femoral Distance
In an attempt to find a more reliable tool for discrimination between symptomatic patients and healthy individuals, anterior femoral distance (AFD), femoral distance (FD), and offset were suggested as alternative methods to the $\alpha$ angle for measuring cam-type deformities (Fig. 15).

Anterior femoral distance: The AFD method was introduced by Lohan et al. as an alternative MRI measurement of femoral neck overgrowth (performed in a MR arthrographic study using the axial oblique sequence along the center of the femoral neck when cross-referenced to coronal images through the hip, ensuring that the fovea capitis was visible). AFD corresponds to the perpendicular distance between a line drawn along the cortex of the anterior aspect of the anterior femoral neck and the point of maximal FHN overgrowth.

Femoral distance: Ehrmann et al. developed and adapted AFD measurement, where FD was measured between a line through the cortex of the femoral neck parallel to the central axis of the neck and the point of greatest femoral head-neck overgrowth (around the FHN). Larger FD values indicate the presence of a cam-type deformity. They confirmed that the best position for AFD measurement/discrimination in cam-type FAI is the anterosuperior segment.

Lohan et al. considered AFD values $> 3.6$ mm to be abnormal. Ehrmann et al. suggested a lower FD threshold in the anterior and anterosuperior position $> 2.2$ mm. Using a higher threshold than 2.2 mm resulted in a higher sensitivity but distinctly decreased specificity for discriminating asymptomatic individuals and patients with cam-type deformities (online Supplementary Table 2). Overall, ICC was reported as good (offset: 0.657/FD 0.632).

However, neither offset nor FD measurements individually offer an advantage over the $\alpha$ angle for assessing the FHN junction in patients with suspected FAI.

Femoral Neck-Shaft Angle
General Considerations
The femoral neck-shaft angle (NSA), or caput-collum-diaphyseal angle, is an anatomical measure for the geometric assessment of the proximal femur. The biomechanical and...
clinical significance of the NSA is underlined by its involvement in the decision-making process for hip-preserving surgery. It is routinely assessed in pediatric orthopaedics during the management of DDH and Perthes disease as well as in the planning of fracture treatment and osteotomies. A hip with a varus femoral neck (< 120 degrees) was reported as being subjected to higher mechanical stress, greater risk of labral tears, and prone to developing early symptoms.

Methodology of NSA measurement, defined as the angle between the FNA and femoral long axis, varies significantly in the literature because hip rotation along with femoral torsion influence the projected NSA on radiographs (at least four different methods were described for pelvis radiographs) (►Fig. 16).

Due to rotational influences and imprecise positioning of the femoral shaft and neck axis, reliability of the NSA measured on AP XR was challenged. Although AP XR is susceptible to rotational errors, CT or MRI-based coronal reconstruction of the proximal femur along the femoral neck plane can conceptually allow the correct measurement of the NSA. In a XR-based systematic review, the intraobserver and the interobserver correlation coefficients ranged between 0.76 and 0.95 and 0.58 and 0.89, respectively. The difference between the rotation-corrected NSA and noncorrected measurements was reported to be 1 degree in a XR systematic review and 2.87 degrees in a CT-based study. Boese et al found significantly higher NSA values in the simulated pelvic AP XR (noncorrected in the APP) when compared with the exact coronal reconstructions (however no more than ~ 3 degrees).

Age and sex influence the NSA although to a small extent (no more than 2-4 degrees between age extremes and the sexes). Varus hips increase with age in both sexes. Higher mean NSA values are seen in females compared with males.

Thresholds

There is a high variability of reported NSA RefInt, mainly due to the variability of measurement methods used and to a lesser extent on account of rotation-correction variations.

Mean NSA values between 129 and 132 degrees were observed in some recent XR- and CT-based reviews in large cohorts. As such, a 95% RefInt between 120 degrees and 140 degrees can be considered the expected epidemiological RefInt (online ►Supplementary Table 3).

Interestingly, in the presence of a cam morphology, a decreased NSA was acknowledged as a useful parameter to identify hips at risk of symptomatic FAI.

Triangular Index

Gosvig et al demonstrated that cam morphology of the FHN may be detectable on standardized AP pelvic and/or lateral radiographs when applying the triangular index (TI) (►Fig. 17). This method provides an additional description of the cam morphology in both radiographic projections, although it is difficult to use in clinical practice.

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Fig. 16 Neck-shaft (NSA) angle measurements. (a) Right hip computed tomography reformat. (b) Right hip anteroposterior pelvic radiograph. Femoral neck axis (FNA) and femoral long axis (FLA). FNA is usually defined by a line connecting the femoral head center (FHC) and the femoral neck center (FNC). The FHC is usually the center of a circle defined by three points around the circumference of the femoral head (that can be challenging in hips with head deformity). The FNC can be defined reproducibly by the proposed method of Müller as the center between the cutting points of a circle centered on the FHC and the lower and upper margin of the waist segment of the femoral neck. To define the FLA, the best reproducibility can be expected by using the method of Clark et al, represented by a line crossing the center of two circles placed in the femur at two positions. The center of the first circle is positioned at the level of the lesser trochanter and the second circle 2 cm below the first. The circles should coincide with the outer margins of the femur.
The \( \Omega \) angle can be more easily obtained from 3D images, calculating the clockwise 360-degree \( \alpha \) angle. The \( \Omega \) angle is formed by measuring the angle corresponding to the three points formed by the center of the femoral head, the point where the \( \alpha \) angle begins to be abnormal beyond a best fitting circle, and the final one where the \( \alpha \) angle returns to a normal value\(^{27} \) (Fig. 13).

This novel quantitative measure was shown to have diagnostic\(^{27,53} \) and treatment-planning\(^{110} \) capabilities. The importance of this parameter was additionally outlined by an arterial topographic study of the proximal femur.\(^{111} \)

**Thresholds**

Mascarenhas et al found that symptomatic patients have larger cam deformities (defined by increased \( \Omega \) angles and \( \alpha \) angles) than asymptomatic volunteers. Mean \( \Omega \) angle differences of \( 27 \pm 24 \) degrees (asymptomatic) versus \( 66 \pm 32 \) degrees (symptomatic patients) were depicted, with an optimal \( \Omega \) angle threshold of 43 degrees (sensitivity 72%, specificity 70%; AUC: 0.830) observed as one of the best parameters to discriminate asymptomatic from symptomatic hip patients.\(^{53} \)

**Key Points**

1. Although other 2D parameters exist to appreciate FHN morphology, to date none has demonstrated superiority to the \( \alpha \) angle.
2. The \( \Omega \) angle has a supplementary role to the \( \alpha \) angle because it measures the radial span of a cam morphology.

**Omega Angle**

**General Considerations**

XR, CT, and MRI techniques for measuring cam-type FAIS have until now provided only a 2D characterization of FHN morphology because measurements are made on a limited series of slices,\(^{15} \) and \( \alpha \) angle measurement is performed in only one plane. As such, it is highly dependent on the position at which it is measured.\(^{27} \) Hence MRI and CT 3D reconstructions allow for adequate corrections of femoral head centering and provide a more accurate depiction of femoral morphology.\(^{27} \) The \( \Omega \) angle was introduced by Rego\(^{110} \) on 2D MRI and by Mascarenhas et al\(^{27,51,53} \) on 3D CT and 3D MRI. It is a 3D angular measurement that allows the location and extent of cam morphologies to be quantified (stepping up to a 3D perception of the cam morphology by determining its radial extension). This angle quantifies the extent of abnormally elevated \( \alpha \) angles, providing information on cam magnitude (defined by the radial extension of the FHN deformity). Significant positive correlations are seen between the \( \Omega \) and \( \alpha \) angles (increasing values of the \( \alpha \) angle correlate to higher values of the \( \Omega \) angle).\(^{27} \)

**Femoral Torsion**

**General Considerations**

Femoral torsion represents the amount of rotation or torsion between the proximal and distal parts of the femur. It is the angle between two planes: the plane through the long diaphyseal axis of the femur (LFA) (parallel to the line connecting the dorsal aspect of the medial and lateral femoral condyles) and the plane containing the FNA.\(^{112} \) This angle is usually positive; that is, the femoral neck is normally anteverted in relation to the axis of the femoral condyles.

Abnormalities of femoral torsion have been investigated for decades and associated with several hip disorders, such as hip dysplasia, slipped capital femoral epiphysis, or OA.\(^{113,114} \) More recently, they were the focus of renewed attention due to their relation with several types of hip impingement,\(^{115,116} \) particularly the combination of cam-type FAIS with reduced torsion,\(^{117} \) because decreased femoral torsion may exacerbate\(^{118} \) or even outweigh\(^{119} \) the effect of a cam morphology and further impair hip internal rotation, aggravating early femoroacetabular contact.
In a study carried out by Lerch et al., every 1 in 6 patients with hip pain attributed to FAI or DDH presented with an abnormal femoral torsion. They also found abnormal values of torsion in 74% of symptomatic hips where no obvious pathomorphology could be detected on radiographs. In fact, rotational deformities, along with cam- and pincer-type morphologies, are now considered one of the three major osseous contributors to FAI. Accordingly, because abnormalities of femoral torsion may cause damage to the hip and affect outcomes of hip-preserving surgery, excessive anteversion or retroversion may need to be addressed surgically by derotational osteotomies. Thus assessment of torsion in young patients with hip pain is mandatory.

Interestingly, patients with pincer-type FAIS have a larger femoral antetorsion than patients with cam-type FAIS, although this parameter per se does not differ significantly between symptomatic and healthy individuals. Recently, the supra- and infra-trochanteric components of femoral torsion were demonstrated to differ substantially between hip disorders because patients with DDH have predominantly increased infra-trochanteric torsion, whereas patients with pincer-type FAIS have increased supra-trochanteric torsion.

Femoral torsion decreases significantly from birth until skeletal maturity, remaining stable afterward. An association with side and sex was also reported, with lower antetorsion values on the right hip and in males compared with females.

Initially, femoral torsion was measured on radiographs, but CT and MRI are currently the preferred modalities to determine this parameter. Although a globally accepted measurement method remains to be ascertained, adequate anatomical measurements of femoral torsion can be performed on CT and MRI systematically using strict axial slices. Biplanar radiographs with 3D modeling are being increasingly used for torsional assessment and constitute a low-dose alternative to CT with comparable results. The 3D-based measurements were reported to be reproducible and independent of femur positioning, overcoming major reproducibility issues encountered with 2D methods.

Various measurement methods are reported in the literature for assessing this angle. Although defining the axis of the femoral condyles is consensual, the definition of the FNA has been extensively debated, and at least five methods can be used.

One method (Jarret et al) uses oblique axial slices of the proximal femur, parallel to the femoral neck, instead of the standard strict transverse plane. This method allows drawing the FNA more quickly because the whole femoral neck can be visualized on a single slice, but it yields slightly lower values of femoral antetorsion. A trigonometric conversion formula was described, and an online converter is available (femoral antetorsion converter, available at http://www.antetorsion.org). Accessed November 20, 2018), which may accurately predict the standard measurements using the oblique axial values.

The other four methods define the FNA either by using a single axial slice through the neck (Lee et al) or two axial slices, in which one passes through the femoral head and the other through the center of the greater trochanter (Tomczak), at the level of the lesser trochanter center (Murphy et al) or at the center of the femoral neck (Reikeras). Interestingly, the more caudal this angle is measured, the higher the values of torsion are obtained.

Thresholds

Normal values of femoral torsion angles reported in the literature vary significantly. This is largely related to the method of measurement used (as previously stated, specifically to differences in how the center of the neck and proximal femoral axis are defined). Inter- and intraobserver variability may also account for the wide range of normal values reported in the literature. In addition, 2D measurements of 3D structures are prone to bias. Although not used routinely in clinical practice, automated analysis software may in the future help overcome some of these issues.

The choice of imaging technique also matters. Although high correlation was found between CT- and MRI-based measurements, there is a trend toward slightly higher absolute values on CT. Therefore, reference intervals of femoral torsion depend on the imaging modality and method of measurement used, and it may be necessary to apply different thresholds accordingly.

Tönnis and Heinecke et al estimated that 15 to 20 degrees is the normal range for femoral antetorsion based on XR and CT data. and Sutter et al reported mean values of 12.8 ± 10.1 degrees in asymptomatic adults using MRI. Other authors obtained similar results in symptomatic and asymptomatic adults using the Reikeras et al technique (online - Supplementary Table 4).

Spinopelvic Parameters

General Considerations

Sagittal (spinopelvic) balance of the spinal column is an evolutionary adaptation that became necessary for humans to adopt a vertical posture. The spine and pelvis have a synergistic relationship, and studies showed that a link exists between these structures and the development of spine pathology.

In 1992, Duval-Beaupère et al first established an anatomical parameter they named the “angle of sacral incidence” that later became known as “pelvic incidence” (PI). This parameter is defined as the angle between the line perpendicular to the sacral plate at its midpoint and a line from the midpoint between the axis of the two femoral heads to the center of the upper surface of the sacrum.

Besides PI, two other morphometric spinopelvic parameters have been described that are interrelated, namely, sacral slope (SS) and pelvic tilt (PT) (Table 5).

PT and SS are dynamic parameters that change with hip motion and position. PI, in contrast, is a fixed parameter for
each individual. In brief, PT and SS depend on posture (higher SS when supine and lower when standing) and conjointly compose PI, which is an individual position-independent angle. This dynamic “unit” may change in response to postural changes to maintain vertebral and pelvic sagittal balance.\textsuperscript{134} (\textit{Fig. 19}).

Spinopelvic parameters (SPPs) can be measured using lateral lumbosacral radiographs,\textsuperscript{135,136} pelvic CT images,\textsuperscript{137} and pelvic MRI.\textsuperscript{53,138} Very few studies have addressed differences between measurements on distinct imaging modalities; Moon et al.\textsuperscript{139} found an increase in SS and a decrease in PT and PI (SS increased by 3.5 degrees, PT decreased by 6.7 degrees, and PI decreased by 3.2 degrees) when comparing XR and CT measurements, which might be associated with positional and methodological changes. Variability in standing to sitting position was described for PT,\textsuperscript{140} and difference in measurements pertaining to XR (standing) and CT (decubitus) modalities were studied for all spinopelvic parameters.\textsuperscript{139} MRI and CT 3D reconstructions allow for adequate corrections of femoral head centering and could provide a more accurate depiction of pelvic morphology.\textsuperscript{53}

With regard to pathology, there is a direct relationship between lumbar lordosis and SS, and a strong positive correlation between PI and sacral kyphosis was identified.\textsuperscript{141} Han et al. concluded that a high PI value in patients with degenerative lumbar scoliosis might be associated with the high prevalence of degenerative lumbar spondylolisthesis. Also, in patients with isthmic spondylolisthesis, greater SPP values are associated with a greater slip grade.\textsuperscript{142}
Demographic factors were reported to influence SPP, namely, sex and age, however with contradictory results. Higher PT and PI were reported, although not universally, in female subjects. Interestingly, Mascarenhas et al found higher SS and PI in asymptomatic females compared with asymptomatic males, whereas opposite observations were depicted when only considering symptomatic subjects. Some authors concluded that pelvic parameters are not statistically different between sexes. With respect to age, PI and PT were found to increase with age. Similarly, Mac-Thiong et al described a weak correlation of spinopelvic parameters with age. Some studies showed no statistically significant difference. Others also found an increased PT and decreased SS with aging.

Evaluation among different ethnic groups showed that mean PI is similar in Japanese and lower in Mexicans and Asians as compared with whites. Zhu et al found that subjects from Chinese population had a significantly smaller PI and SS than those from white populations.

Another study performed between groups with different body mass indices showed that spinopelvic parameters are practically equal among different weight populations.

**Thresholds**

Currently no normative values are established for PI, SS, and PT because there is a high variability of measured values among asymptomatic individuals (online Table S5). Roussouly et al studied 160 individuals and established the following means: 51.9 ± 10.7 degrees for PI, 39.9 ± 8.1 degrees for SS, and 11.9 ± 6.4 degrees for PT, respectively. A study performed among 709 asymptomatic adults without spinal pathology established similar values for PI (52.6 ± 10.4 degrees), SS (39.6 ± 6.8 degrees) and PT (13.0 ± 6.8 degrees).

Relationship of sagittal balance and hip disorders is currently controversial. PI is an indicator of acetabular retroversion, and patients with a higher PI have more anteriorly positioned femoral heads and a better ability to compensate for sagittal imbalance with pelvic retroversion. Sagittal rotation also changes the socket orientation of the acetabulum, contributing to or protecting from FAI: The L-CEA and percentage of acetabular crossover increases with pelvic forward tilt and decreases with back tilt.

FAIS patients were recently shown to have higher PI and SS angles. Recently, Mascarenhas et al showed that increased SPPs are predictive of a hip symptomatic state, and Ng et al corroborated this finding for PI. A significant contribution of these parameters for a symptomatic hip and OA was suggested. In fact, decreasing values of SS may allow greater impingement-free hip flexion by effectively reducing femoral coverage anteriorly. Saltychev et al, however, challenged this relationship as not showing evidence of a substantial role of pelvic incidence in hip.

**Table 5** Spinopelvic parameters: definition of pelvic incidence, sacral slope, and pelvic tilt

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Radiograph</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>(angle)</td>
<td>Standing sagittal lumbosacral</td>
<td>Angle between the line perpendicular to the sacral plate at its midpoint and a line from the midpoint between the axis of the two femoral heads to the center of the surface of the sacrum ( PI = SS + PT )</td>
</tr>
<tr>
<td>SS</td>
<td>(angle)</td>
<td>Standing sagittal lumbosacral</td>
<td>Angle formed by a line drawn parallel to the end plate of the sacrum to a horizontal reference line</td>
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<tr>
<td>PT</td>
<td>(angle)</td>
<td>Standing sagittal lumbosacral</td>
<td>Angle formed by a line from the midpoint of the sacral end plate to the center of the femoral heads and a vertical plumb line</td>
</tr>
</tbody>
</table>

Abbreviations: PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope.

**Fig. 19** Imaging spinopelvic parameters. – Table S5 lists the definitions. PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope.
disorders, suggesting a possible association of lower PI with FAI.

**Key Points**

1. Femoral torsion determination is mandatory in the young adult hip because it is one of the three major osseous factors that can lead to the development of FAIS. Its thresholds vary greatly with the measurement method used (consistency is recommended).
2. Spinopelvic parameters are increasingly recognized as a major contributor (fourth contributor along with cam, acetabulum morphology, and femoral torsion) to hip pathology.

**Conclusion and Future Directions**

The totality of the information presented in this synopsis, addressing imaging of the hip joint, shows that we have gained an enhanced ability to assess the problematic hip. From defining normal anatomy to identifying critical lesions, the current diagnostic modalities will continue to play an important role in the clinician’s armamentarium. With a standardized approach and technique, the causes of hip dysfunction and disability can be identified successfully. Likewise, as our understanding of anatomical structures and pathologic findings in the symptomatic hip improve, the understanding of the indications for imaging modalities, definitions of normative values, and assessment of pertinent findings will also improve. It is not uncommon to identify “pathologic” findings in the asymptomatic population, and determining which imaging findings are associated with symptoms and require intervention will become an increased point of emphasis in the future.53

The future of imaging of the hip will build on the defined parameters of the modalities discussed here. For example, the ability to identify early cartilage lesions with the use of T2 cartilage mapping sequences and delayed gadolinium-enhanced MRI will aid the clinician to identify the at-risk hip.154 In these particular cases, enhanced surveillance with cost-effective imaging modalities will enhance patient care by facilitating early detection of injury and possibly treatment. Furthermore, the improved definition of the relationship between hip conditions and spinopelvic parameters will enable the clinician to optimize patient selection for specific treatments (surgical and nonsurgical).55 The promise of future improvements in imaging also leads one to ponder the prospects of correlating imaging findings with histologic findings or even with biomarkers of cartilage or soft tissue damage.155 This ability to correlate imaging with physiology is perhaps the next frontier. Likewise, correlating the outcomes of treatments such as surgery with postintervention imaging holds promise in helping the clinician assess the impact of intervention. If current challenges are met through focused investigation and directed innovation, it will be possible to continue enhancing patient care and clinical understanding of the hip joint.

**Conflict of Interest**
None declared.

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