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Which acetabular measurements most accurately differentiate between patients and controls? – A comparative study

Running title: **Thresholds for acetabular morphology to guide management**

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Abstract

Background Acetabular morphology is an important determinant of hip biomechanics. To identify features of acetabular morphology that may be associated with the development of hip symptoms, while accounting for spinopelvic characteristics, one needs to determine acetabular characteristics in a group of individuals older than 45 years without symptoms or signs of osteoarthritis. Previous literature has used patients with unknown physical status to define morphological thresholds to guide management.

Questions/purposes This study aimed to (1) determine acetabular morphological characteristics in males and females between 45 to 60 year-old with a high Oxford Hip Score (OHS) and no signs of osteoarthritis, (2) compare these characteristics with those of symptomatic hip patients treated with hip arthroscopy or peri-acetabular osteotomy (PAO) for various kinds of hip pathology (dysplasia, retroversion, and cam Femoro-Acetabular Impingement); and (3) assess which radiographic or Computed Tomography (CT) parameters most accurately differentiate between patients who had symptomatic hips and those who did not; thus, define thresholds that can guide management.

Methods Between January 2018 and December 2018, 1358 patients underwent an abdomino-pelvic CT scan in our institution for non-orthopaedic conditions. Of those, we considered 73 patients (5%) as potentially eligible as controls based on the absence of major hip osteoarthritis, trauma or deformity. Patients were excluded if OHS ≤ 43 (n=28), a PROMIS <50 (n=18), or Tönnis score ≥1 (n=6), Another 16 hips were excluded due to insufficient datasets. After randomly selecting one side for each control, 40 hips were left for analysis (age 55±5 years; 48% [19 of 40] were women). In this comparative study, this asymptomatic group was compared with

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a group of patients treated with hip arthroscopy or PAO. Between January 2013 and December 2020, 221 hips underwent hip preservation surgery. Of those, 8 were excluded due to previous pelvic surgery, and 102 because of insufficient CT-scans. One side was randomly selected in patients who underwent bilateral procedure, leaving 107 hips (48%) for analysis (age 31±8 years; 54% [58 of 107] were women). Detailed radiographic and CT assessments (including segmentation) were performed to determine acetabular (depth, cartilage coverage, subtended angles, anteversion, and inclination) and spinopelvic (pelvic tilt and incidence) parameters. Diagnostic accuracy and thresholds to differentiate between symptomatic patients and asymptomatic controls were assessed with a receiver operating characteristic analysis.

Results Acetabular morphology in asymptomatic hips was characterized by a mean depth of 22±2 mm, with an articular cartilage surface of 2619±415mm^2, covering 70±6% of the articular surface, a mean acetabular inclination of 48° ± 6° and a minimal difference between anatomical- (24±7°) and functional- (22±6°) anteversion. Patients with symptomatic hips generally had less acetabular depth (20±4 mm vs. 22±2 mm, mean difference 3 mm [95% CI, 1 to 4 mm]; $p < 0.001$). Hips with dysplasia (67±5% vs. 70±6%, mean difference 6% [95% CI, 0 to 12%]; p=0.031) or retroversion (67±5% vs. 70±6%, mean difference 6% [95% CI, 1 to 12%]; p=0.044) had a slightly lower relative cartilage area compared to asymptomatic hips. There was no difference in acetabular inclination (48±6° vs. 47±7°, mean difference 0.5° [95% CI, -2 to 3°]; p=0.35), but asymptomatic hips had higher anatomic anteversion (24°±7° vs. 19±8°, mean difference 6° [95% CI, 3 to 9°]; p<0.001) and functional anteversion (22±6° vs. 13±9°, mean difference 9° [95% CI, 6 to 12°]; p<0.001). Subtended angles were higher in asymptomatic at 105° (124±7° vs. 114±12°, mean difference 11° [95% CI, 3 to 17°]; p<0.001), 135° (122±9° vs.

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111±12°, mean difference 10° [95% CI, 2 to 15°]; p<0.001) and 165° (112±9° vs. 102±11°, mean difference 10° [95% CI, 2 to 14°]; p<0.001) around the acetabular clockface. Symptomatic hips had a lower pelvic tilt (8±8° vs. 11±5°, mean difference 3° [95% CI, 1 to 5°]; p=0.007). The posterior wall index had the highest discriminatory ability of all measured parameters, with a cutoff value of <0.9 (AUC 0.835; 95% CI, 0.763 to 0.907) for a symptomatic acetabulum (sensitivity 74%; specificity 78%). Diagnostically useful parameters on CT scan to differentiate between symptomatic and asymptomatic hips were acetabular depth <22 mm (AUC 0.743; 95% CI, 0.658 to 0.829), and functional anteversion <19° (AUC 0.791; 95% CI, 0.716 to 0.867). Subtended angles with the highest accuracy to differentiate between symptomatic and asymptomatic hips were those at 105° (AUC 0.760; 95% CI, 0.646 to 0.875), 135° (AUC 0.783; 95% CI, 0.703 to 0.863) and 165° (AUC 0.769; 95% CI, 0.688 to 0.849) of the acetabular clockface.

Conclusion An anatomical and functional acetabular anteversion of 24° and 22°, with a pelvic tilt of 10°, increases acetabular opening and allows for more impingement-free flexion, whilst providing sufficient posterosuperior coverage for loading. Hips with lower anteversion or a larger difference between anatomic and functional anteversion are more likely to become symptomatic. The importance of sufficient posterior coverage was also illustrated by the PWI and subtended angles at 105°, 135° and 165° of the acetabular clockface having a high discriminatory ability to differentiate between symptomatic and asymptomatic hips. Future research should confirm whether integrating these parameters in selecting patients for hip preservation procedures can improve post-operative outcome.

Level of Evidence Level III, prognostic study.

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Introduction

Acetabular morphology is an important determinant of joint biomechanics. Deficient coverage (dysplasia) can lead to excessive rim loading [36, 44], while increased coverage (pincer morphology or retroversion) may lead to femoroacetabular-impingement (FAI), resulting in labral and cartilage degeneration in some patients [18, 19, 62]. Adequate surgical correction through acetabular rim trimming (FAI) or periacetabular osteotomy (dysplasia or retroversion) can reduce pain, improve function [24, 41, 45, 59], and postpone arthroplasty in patients with these morphologies if their hips become painful [32, 49].

Acetabular morphology is complex and highly variable [10, 23, 29]. Conventional diagnostic criteria based on two-dimensional imaging might underestimate or fail to detect subtle abnormalities [61]. Computed tomography (CT) with three-dimensional reconstruction allows for better characterization, and can account for pelvic tilt, rotation, and obliquity [51]. Furthermore, additional characteristics such as the ratio between acetabular cartilage and fossa areas [47] and spinopelvic characteristics, which influence pelvic tilt and acetabular orientation [12, 30], are considered important predictors of symptomatic hip disease [23, 27, 40].

Individuals who have entered middle-age (between 45 and 60 years-old [24, 35, 43]) without hip symptoms, nor signs of osteoarthritis, can help to characterize acetabular morphology, create benchmarks of parameters to assess in the diagnostic work-up, and determine what surgical correction to aim for. Previous studies have used patients in poor physical condition (with malignant disease[2] or knee osteoarthritis[17]) or with unknown functional status to define acetabular morphology [7, 10, 29, 57]; furthermore, when activity levels were known, analyses were based on radiographs, thus lacking comprehensive 3D assessment [3, 4].

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This study therefore aimed to (1) determine acetabular morphological characteristics in males and females between 45 to 60 year-old with a high Oxford Hip Score (OHS) and no signs of osteoarthritis, (2) compare these characteristics with those of symptomatic hip patients treated with hip arthroscopy or peri-acetabular osteotomy (PAO) for various kinds of hip pathology (dysplasia, retroversion, and cam Femoro-Acetabular Impingement); and (3) assess which radiographic or Computed Tomography (CT) parameters most accurately differentiate between patients who had symptomatic hips and those who did not, and define thresholds for these parameters that can guide management.

Patients and Methods

Study Design and Setting

This was an institutional review board-approved, retrospective comparative study, conducted at a single tertiary-referral academic center with a hip preservation unit (the Ottawa Hospital, Ontario, Canada).

Cohort Description

Asymptomatic Group

Between January 2018 and December 2018, 1358 patients underwent an abdomino-pelvic CT scan in our institution for non-orthopaedic conditions. Participants between 45 and 60 years old were chosen, as these have passed through young adult years without experiencing pain or degenerative changes while maintaining high activity levels because they can help to define thresholds of morphological parameters that can guide management. Furthermore, age of 45 years is considered an important threshold age for hip preservation surgery [24, 35, 43]. Of those, we considered 73 patients (146 hips) (5%) as potentially eligible as controls based on the absence of major hip osteoarthritis, trauma or deformity. The asymptomatic group had, partially, been used in a previous study [13], and further selection based on symptoms and daily life functioning was done for the current study. These patients were contacted by telephone or email and answered standardized and validated questionnaires regarding hip and overall function, including the Oxford Hip Score (0-48) [11, 38], and Patient-Reported Outcome Measurement Information System (PROMIS) general and mental health score (0-100) [16]. Patients were excluded if they had an Oxford Hip Score ≤ 43 (14 patients; 28 hips) or a PROMIS score < 50 (nine patients; 18 hips). No patients had a history of spinal surgery or deformity on lateral

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spinopelvic radiographs. A musculoskeletal radiologist (K.R.) reviewed all images and graded the degree of degeneration using the Tönnis score [7, 29, 55]. Any hip with Tönnis grade > 1 was excluded (three patients; six hips). Eight additional patients (16 hips) were excluded because the acetabulum was not completely included or CT axial slice thickness was > 2.5 mm. From each patient one side was randomly selected, leaving 40 hips for inclusion (Fig. 1).

Patient Group

The hips of patients who underwent hip preservation surgery (defined as hip arthroscopy for cam FAI, or Peri-Acetabular Osteotomy (PAO) for hip dysplasia or acetabular retroversion) by one of two-fellowship trained orthopaedic surgeons (P.B. & G.G.) between January 1, 2013, and December 31, 2020 were considered potentially eligible for this study; this group consisted of 221 hips in 209 patients. Patients underwent preoperative pelvic CT but were excluded if they had previous pelvic surgery (eight hips; eight patients), if scans did not include the sacral endplate, or if slice thickness was > 2.5 mm (102 hips; 100 patients). No patients had a history of spinal surgery or deformity on lateral spinopelvic radiographs. In patients with previous bilateral surgery, one side was randomly selected, leaving 107 hips for inclusion (Fig. 1). Of those, 41% were treated with hip arthroscopy for cam FAI (44 of 107), 34% with PAO for hip dysplasia (36 0f 107) and 25% with PAO for retroversion (27 of 107).

Descriptive Data

Symptomatic patients were younger than asymptomatic controls (31±8 versus 55±5 years; p < 0.001), but there were no differences in the sex distribution between groups (54% [58 of 107] versus 48% [19 of 40] female; p = 0.47) (Table 1).

Radiographic Assessment

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Patients underwent radiographic assessment with supine AP pelvic radiographs [8]. Radiographic assessments of controls were performed using reconstructed images from CT (scout view). Parameters measured included lateral center-edge angle (LCEA) [60], acetabular index (AI) [54], signs of acetabular retroversion (crossover sign, posterior wall sign, and ischial spine sign) [42], and the anterior and posterior wall indices (AWI and PWI) [46]. Alpha angle was measured [39] on 45° Dunn radiographs.

One resident orthopaedic surgery performed all measurements (Z.D.). Measurements were repeated for 20 of randomly selected datasets (15%) in a blinded fashion by a fellowship-trained hip preservation surgeon (J.V.). Inter-observer reliability was calculated using average correlation coefficient with a two-way mixed model. Intra-class coefficient >0.75 was considered to have excellent reliability (0-1: no – absolute agreement)[15] (Appendix A).

CT Imaging Assessment

CT scanning was performed with 64-slice scanners (GE Healthcare, Revolution or Discovery HD750). Positioning was standardized with no leg abduction or adduction and leg internally rotated with patellae facing upwards. Scans were exported from institutional Picture Archiving and Communication System and analyzed with ITK-SNAP analysis software (ITK: The Insight Segmentation and Registration Toolkit). A brief description of the analysis is described below, but has been described in detail previously [12, 40].

Acetabular Characteristics

Acetabular segmentation began by defining the region of interest. An automatic bone segmentation procedure was applied to generate a pelvic surface model [48]. The acetabulum was defined through an iterative process. The edges of the spherical loading region were detected

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using local variation of the normal surface, and the surface model was clipped to these edges. A best-fit sphere was calculated from the nodes of the resulting surface mesh. Sphere parameters were used to refine the previous spherical clip, and the process was repeated until changes in the sphere center were less than 0.1 mm. The portions of the acetabulum and cotyloid fossa were then separated using edge detection (Fig. 2). The relative articular cartilage area was calculated by dividing the cartilage area (bearing surface minus fossa area) by bearing surface area.

To determine the degree of femoral head coverage by the acetabulum, subtended angles were calculated. First, the hip joint center was defined by a least-squares best-fit sphere of the subchondral segment of the acetabulum, where the radius of the sphere represents the size of the acetabulum. Subtended angles were defined as the angle between the bicoxofemoral axis, a line connecting both hip joint centers, and a line between the hip joint center and acetabular rim point (Fig. 3) [13], rather than the acetabular rim plane and rim point as previously described [10, 40], which is sensitive to acetabular version. Subtended angles were calculated around the weightbearing, acetabular clockface with increments of 30° from anterior to posterior.

A plane was created through the anterior-superior iliac spine (ASIS) and pubic tubercles, defining the anterior pelvic plane (APP) [23, 30]. The APP angle (APPA) was defined as the angle between APP and horizontal. Next, points around the rim were identified directly on axial CT slices and a least-squares best fit plane was calculated from these points to define the acetabular rim plane [34]. The best-fit sphere of the acetabulum was used to calculate the acetabular depth as the perpendicular distance from acetabular rim plane to this best-fit sphere. The angle between the acetabular rim plane and the projection of the vertical plane in the coronal plane defined *acetabular inclination* [34, 37]. Acetabular version was calculated relative to two

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planes; morphologic (anatomic) anteversion was relative to the APP (APP plane defined as zero); Functional anteversion was relative to the CT table and horizontal [12].

Spinopelvic Characteristics

Pelvic incidence, sacral slope, and pelvic tilt were determined from pelvic CT reconstructions for both patients and controls (Fig. 4) [31].

Primary and Secondary Study Outcomes

The primary study goal was to describe various acetabular characteristics in asymptomatic patients. Acetabular characteristics included morphological characteristics (acetabular depth, acetabular cartilage area, fossa area and relative cartilage area), orientation (APPA, acetabular inclination, anatomic and functional anteversion, and difference between both), subtended angles at 15°, 45°, 75°, 105°, 135° and 165° around the acetabular clockface, and spinopelvic characteristics (sacral slope, pelvic incidence, pelvic tilt). Differences in acetabular characteristics were compared between males and females.

The second study goal was to compare these parameters between the control group of asymptomatic patients and a symptomatic group of patients treated with hip preservation surgery (hip arthroscopy for cam-FAI or PAO for acetabular dysplasia or retroversion). Comparisons were made between symptomatic and asymptomatic patients, and between different patient subgroups (cam-FAI, dysplasia, retroversion) and asymptomatic patients.

The tertiary study goal was to determine which acetabular parameters, radiographic or CT, could most accurately differentiate between asymptomatic and symptomatic hips, and hereby determine cut-off threshold values for these parameters that can help guiding management.

Ethical Approval

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The study was approved by the institutional review board of our institution and all participants signed an informed consent form for study inclusion.

Statistical Analysis

An a priori sample size calculation based on acetabular subtended angles of 87º ± 4° among controls versus 84º ± 5° among patients [10] determined a minimum of 28 patients would be needed per group to obtain sufficient power ($1-\beta = 0.80$; $\alpha = 0.05$).

Normal distribution was determined using the Kolmogorov-Smirnov test. If data was normally distributed, an independent samples t-test was used to compare continuous variables; if data was not normally distributed, a Mann-Whitney U test was used to compare continuous variables between control and patient groups. Correlation was tested with the Spearman correlation test [22]. A receiver operating characteristic (ROC) curve analysis was used to calculate the area under the curve (AUC) to assess diagnostic accuracy and define thresholds that best differentiate acetabular morphology between symptomatic and asymptomatic patients [25]. Statistical analysis was performed using SPSS version 28 (IBM Corp). A p value < 0.05 was considered significant.

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Results

Morphology of Asymptomatic Hips

Asymptomatic hips were characterized by a mean acetabular depth of 22±2 mm, with an articular cartilage surface of 2619±415mm^2, covering 70±6% of the articular surface (Table 2). Females had a smaller mean articular surface compared to males (2287±307 mm^2 vs. 2920±226 mm^2, mean difference 633 mm^2 [95% CI, 461 to 804 mm^2]; $p<0.001$). However, there was no difference in relative cartilage area between both (70±4% vs. 70±8%, mean difference 1% [95% CI, -11 to 9%]; p=0.86) (Table 3). Mean acetabular inclination was 48° ± 6°, and minimal difference between anatomical- (24±7°) and functional- (22±6°) anteversion was detected. Subtended angles varied between 65° and 124° around the acetabular clockface. Males had lower subtended angles at 135° (125±10° vs. 118±6°, mean difference 7° [95% CI, 1 to 13°]; p=0.02) and 165° of the acetabular clockface males (115±10° vs. 108±6°, mean difference 7° [95% CI, 2 to 12°]; p=0.02). Mean pelvic incidence and pelvic tilt were 54±12° and 11±5°, respectively, with no differences between males and females.

Differences between asymptomatic and symptomatic hips

Patients with symptomatic hips generally had less acetabular depth (20±4 mm vs. 22±2 mm, mean difference 3 mm [95% CI, 1 to 4 mm]; $p < 0.001$). There was no difference in articular cartilage area (2619±415 mm^2 vs. 2479±498 mm^2, mean difference 140 mm^2 [95% CI, -35 to 315 mm^2]; p=0.06) and relative cartilage area (70±6% vs. 69±6%, mean difference 1% [95% CI, -6 to 3%]; p=0.27) between symptomatic and asymptomatic hips (Table 2).

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Hips with dysplasia (67±5% vs. 70±6%, mean difference 6% [95% CI, 0 to 12%]; p=0.031) and retroversion (67±5% vs. 70±6%, mean difference 6% [95% CI, 1 to 12%]; p=0.044) had lower relative cartilage area than asymptomatic hips. Hips with cam FAI had a higher relative cartilage area than asymptomatic hips (72±4% vs. 70±6%, mean difference 5% [95% CI, 0 to 10%]; p=0.030).

There was no difference in acetabular inclination (48±6° vs. 47±7°, mean difference 0.5° [95% CI, -2 to 3°]; p=0.35), but asymptomatic hips had higher anatomic anteversion (24±7° vs. 19±8°, mean difference 6° [95% CI, 3 to 9°]; p<0.001) and functional anteversion (22±6° vs. 13±9°, mean difference 9° [95% CI, 6 to 12°]; p<0.001) compared to symptomatic hips, and a smaller difference between both (2±5° vs. 5±6°, mean difference 3° [95% CI, 1 to 6°]; p<0.001). Cam FAI hips had lower inclination hips (44±5° vs. 48±6°, mean difference 3° [95% CI, 1 to 6°]; p=0.006). Anatomical and functional acetabular version was lower in all patient groups (Table 2), hips with retroversion had the lowest mean anatomic (15±7°) and mean functional anteversion (8±7°).

Subtended angles were higher in asymptomatic compared to symptomatic hips at 105° (124±7° vs. 114±12°, mean difference 11° [95% CI, 3 to 17°]; p<0.001), 135° (122±9° vs. 111±12°, mean difference 10° [95% CI, 2 to 15°]; p<0.001) and 165° (112±9° vs. 102±11°, mean difference 10° [95% CI, 2 to 14°]; p<0.001) around the acetabular clockface (Fig. 5).

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Patients with dysplasia had lower subtended angles between 45° and 165° around the acetabular clockface, and patients with retroversion had lower subtended angles between 105° and 165° of the acetabular clockface (Table 2; Fig. 5).

There was no difference in pelvic incidence (54±12° vs. 52±13°, mean difference 2° [95% CI, -3 to 6°]; p=0.27) between symptomatic and asymptomatic hips. Symptomatic hips had a lower pelvic tilt (8±8° vs. 11±5°, mean difference 3° [95% CI, 1 to 5°]; p=0.007).
Mainly hips with retroversion had a lower pelvic tilt than asymptomatic hips (5±8° vs. 11±5°, mean difference 5° [95% CI, 1 to 9°]; p=0.004).

Diagnostic Thresholds to differentiate between asymptomatic and symptomatic hips

The posterior wall index had the highest discriminatory ability of all measured parameters (Table 4), with a cutoff value of < 0.9 (AUC 0.835; 95% CI, 0.763 to 0.907) for a symptomatic acetabulum (sensitivity 74%; specificity 78%).
Diagnostically useful parameters on CT scan to differentiate between symptomatic and asymptomatic hips were acetabular depth <22 mm (AUC 0.743; 95% CI, 0.658 to 0.829), and a functional anteversion <19° (AUC 0.791; 95% CI, 0.716 to 0.867).
Subtended angles with the highest accuracy to differentiate between symptomatic and asymptomatic hips were those at 105°, 135° and 165° of the acetabular clockface, with cut-off values of 118° (AUC 0.760; 95% CI, 0.646 to 0.875), 119° (AUC 0.783; 95% CI, 0.703 to 0.863) and 109° (AUC 0.769; 95% CI, 0.688 to 0.849) respectively. Radiographic parameters and subtended angles correlated moderately (Table 5).

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Discussion

Determining whether the acetabulum is deficient is an important aspect in the management of the nonarthritic hip, because erroneous diagnosis leads to incorrect surgery and persistent symptoms [6, 20]. The expansion of hip arthroscopy has been associated with its use in patients who would arguably benefit from PAO instead [5, 9]. Providing evidence-based cutoff values of acetabular anatomy can help identifying patients who would benefit from acetabular surgery. This study determined anatomic (coverage, depth, and cartilage area) and functional (orientation and spinopelvic characteristics) parameters that can help with the diagnosis and treatment of hip disorders in young adults. Acetabular characteristics differed between asymptomatic individuals and each patient group. Radiographic parameters were equally sensitive and specific to complex CT measurements, validating their use because they provide important information (best type of treatment offered and degree of intraoperative correction to aim for) when comprehensively used. For example, if an acetabulum does not have an AWI > 0.4, and PWI > 0.9, the possibility of deficiency should be strongly considered, and thus the surgeon should consider alternatives to arthroscopic treatment, perhaps including osteotomy, if the patient is sufficiently symptomatic to justify surgery. Furthermore, these thresholds can be used intraoperatively to guide the amount of correction to aim for. Controls had greater femoral head coverage, primarily posterosuperiorly. This area is of great relevance for load transfer, as stress distribution on the acetabular surface extends more posteriorly during the initial phases of gait [64]. Posterior acetabular deficiency has also been associated with worse outcome after PAO [26] and surgical hip dislocation [50]. Additionally, asymptomatic hips had a greater percentage of cartilaginous surface, illustrating that deficiencies in patients were of cartilaginous, rather than

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noncartilaginous, areas. Although controls had only minimal differences between functional and anatomic anteversion, their anteversion was greater than that in all subgroups (including hips with dysplasia). Moreover, controls had greater posterior pelvic tilt, which increases the acetabular opening, further reducing the risk of impingement [10]; this provides better posterosuperior cover for load transmission, as shown by the respective subtended angles. While a decrease in anterior coverage may reduce risk of impingement, sufficient anterior coverage is needed to avoid excessive anterior rim loading standing and during walking [28].

Limitations

First, the control group was defined, in-part, based on a high OHS and PROMIS score. However, PROM scores are associated with a ceiling effect. Furthermore, the patient cohort was of patients surgically treated, which may have created selection bias as these may represent more severe cases requiring surgical management. However, a large group of young adult hip patients with different types of pathologies and acetabular morphology was compared to asymptomatic controls. This would avoid the formulated thresholds to be subject to the individual surgeons' criteria for surgery. Second, using the APP as reference plane is associated with limitations. Anterior placement of the ASIS is highly variable among individuals, if only because anterior placement of ASIS is a recent evolutionary phenomenon and highly variable in humans relative to the flat ilium of non-human large apes [65]. This may contribute to the high range of APPA values among the different groups. In patients with acetabular retroversion, the entire ilium appears externally rotated on AP pelvic X-rays, influencing position of ASIS and therefore also APP [52]. By uncoupling anatomical and functional anteversion, as well as measuring sagittal

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spinopelvic parameters, we aimed to avoid relying solely on APP in the assessment of acetabular morphology. Third, whilst patients underwent lateral spinopelvic radiographs, radiographs did not include the whole spine. It is possible that abnormalities higher up exist and influence lumbar and spinopelvic characteristics, or that some patients might have had early degenerative changes of the cartilage or intervertebral discs. Fourth, we did not account for femoral head or neck morphology in the control group. CT scans did not extend below the level of the lesser trochanter, nor were the femoral condyles included, which did not allow us to assess for femoral version. We acknowledge the important interaction between femoral and acetabular characteristics [14, 33, 59]. However, the principal aim of this study was to compare acetabular morphology between symptomatic patients and asymptomatic controls, and define thresholds for acetabular morphology. Therefore, femoral rotation and morphology was beyond the scope of this study. Last, all assessments were performed with CT in the supine position, and thus any dynamic changes in functional tilt that may affect degree of coverage were not assessed [17, 56]. The supine position is the standard position of clinical and radiological assessment of young patients with hip pain, and represents the position of the pelvis during surgery. Surgeons should be aware this does not replace the need for a dynamic assessment of pelvic motion, which may also have implications on fragment correction. Furthermore, dynamic spinopelvic characteristics might be age-dependent [58]. However, we only used a control group of volunteers older than 45 years, with minimal expected age-related differences, and we believe any differences are likely to be clinically unimportant [58]. Furthermore, the principal aim of this study was to provide thresholds of morphologic features, and thus a description of compensatory patterns was out of this study's scope.

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Discussion of Key Findings

Young adult hip disorders are typically diagnosed based on radiographic parameters [8, 46]. However, it has been suggested that these parameters are not sufficient to consistently identify different morphologies [29, 51]. The association between acetabular morphology and development of osteoarthritis is recognized for marked deformities, but radiographic cutoff values for normal hips have lacked comprehensive assessments of the studied cohorts [1, 53, 62, 63] (Table 6). Similarly, prior studies aiming to define "normal" acetabular 3D-morphology have used CT images from patients treated for nonorthopaedic conditions, risking the inclusion of symptomatic patients [7, 10, 29, 57] (Table 6). In this study, 2D and 3D assessments were performed to identify thresholds. Radiographic assessments showed good-to-excellent diagnostic ability to differentiate between symptomatic patients and asymptomatic controls. An acetabulum with AWI < 0.4 and PWI < 0.9 could be considered deficient, and therefore such patients are more likely to benefit from PAO than arthroscopic surgery.

Comprehensive assessments provide useful tools to guide practice and management for each of the patient groups studied. Patients with cam FAI had many acetabular features akin to controls, emphasizing that any treatment should predominantly be focused on femoral morphology. Differences in posterosuperior subtended angles were very small, as were differences in functional version and pelvic tilt. These features are likely related. Low functional acetabular anteversion and pelvic tilt seen in cam FAI might be responsible for features of combined (cam and pincer) FAI on plain radiographs (focal crossover sign). If this cross-over sign is misinterpreted, this can mislead surgeons and lead to overtreatment, such as rim-trimming, with

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worse outcome and persistent pain as a consequence [21, 67]. Because anatomic acetabular version and pelvic incidence were not different between cam FAI hips and controls, future studies should test whether postural change with a targeted exercise program can help increase functional acetabular anteversion and reduce the risk of impingement. Patients with dysplasia not only had the expected acetabular undercoverage, but also a lower cartilaginous area relative to the whole acetabular surface. However, the difference was small, while the range of relative cartilage area was large. Therefore, whether this difference is clinically relevant and associated with worse outcome and persistence of hip pain after joint preserving surgery ought to be studied further. Furthermore, this study provides important surgical targets for PAO when aiming to reproduce the normal acetabular anatomy as closely as possible. Lastly, hips with acetabular retroversion showed increased anterior coverage and reduced posterosuperior coverage relative to controls. In such cases, both phenomena are likely to occur: Anterior impingement results from pincer and posterosuperior dysplasia, leading to instability. However, which one is the predominant feature might be patient-specific and dependent on other factors (femoral morphology, activities of daily living, or others). However, caution is recommended in cases when the surgeon considers arthroscopic acetabular rim trimming, because this might render the acetabulum deficient, increasing the load on an already reduced surface area [10, 66]. Some of these findings might also be a function of the reduced pelvic tilt in symptomatic hips compared with controls. However, hips with retroversion have shown little or no ability to adjust pelvic tilt [22], and thus the acetabular morphology should be addressed. In the future, dedicated software might expedite 3-D analysis to create such contour plans more easily and help with diagnosis and treatment.

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Conclusion

This study compared acetabular morphology of asymptomatic controls and patients treated with hip preservation surgery. An anatomical and functional acetabular anteversion of 24° and 22°, with a pelvic tilt of 10°, increases acetabular opening and allows for more impingement-free flexion, whilst providing sufficient posterosuperior coverage for loading. Hips with lower anteversion or a larger difference between anatomic and functional anteversion are more likely to become symptomatic. The importance of sufficient posterior coverage was also illustrated by the PWI and subtended angles at 105°, 135° and 165° of the acetabular clockface having a high discriminatory ability to differentiate between symptomatic and asymptomatic hips. Radiographic measurements were not inferior to CT measurements when differentiating between patients and controls. Thresholds of AWI (0.4) and PWI (0.9) can accurately identify the presence of deficient acetabular morphology. These findings are important during diagnostic assessment of young adults presenting with hip pain and when determining treatment plan. Furthermore, these features create benchmarks for optimal acetabular positioning during PAO. Future studies should confirm whether integrating these parameters in selecting patients for hip preservation procedures lead to improved post-operative outcome.

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Legends

Fig. 1 This flowchart shows the inclusion process.

Fig. 2 This figure shows the segmentation process to determine acetabular morphology. (A) First, the region of interest is defined and (B) the segmented femur is removed. (C and D) The pelvis is then manually clipped with a sphere to retain the acetabulum and rim. (E and F) The acetabular load-bearing region and cotyloid fossa are delineated by detecting local changes in surface orientation to define edges, and a best-fit sphere is determined.

Fig. 3 This figure shows the different acetabular subtended angle locations along the acetabulum.

Fig. 4 This figure illustrates how spinopelvic characteristics, including sacral slope (SS) and pelvic incidence (PI), were measured.

Fig. 5 This figure illustrates values for the different subtended angles around the acetabular clockface for (A) contols and symptomatic patients; and (B) for controls and subgroups of patients with different hip disorders.