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Research Article

Anatomical Variations of the Acetabulum and Their Implications for Total Hip Arthroplasty: a Multicenter CT-Based Study

Malik Muhammad Yassin Awan[1*], Shamaila Ejaz[2], Muhammad Adeel Razzaque[3], Samina Ashraf[4], Hira Anwar[5], Samar Ashraf[6]

[1*]Associate Professor. Orthopedics Department. Sahara medical college. Narowal.
[2]Assistant professor. Anatomy Department. Lahore Medical and Dental college, Lahore.
[3]Associate Professor. Orthopaedic department. Bakhtwar Amin Medical & Dental College. Multan.
[4]Senior Demonstrator. Anatomy Department. Faryal Dental College Sheikhupura.
[5]Demonstrator. Anatomy Department. Muhammad Medical College, Mirpurkhas.
[6]Professor of Anatomy. King Edward Medical University. Lahore.

Corresponding Author: Malik Muhammad Yassin Awan
Associate Professor. Orthopedics Department. Sahara medical college. Narowal.
Email: [1]Orthoandyasin@yahoo.com, [2]sijaz47@gmail.com, [3]adeelsurgeon@gmail.com, [4]drsaminaashraf@gmail.com, [5]bhambhro39@gmail.com, [6]samarashraf999@gmail.com

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ABSTRACT

Objective: To determine anatomical variations in acetabular morphology using computed tomography and evaluates their implications for total hip arthroplasty in a resource-constrained healthcare setting.

Methods: This multicenter retrospective cross-sectional study included 204 adults whose pelvic computed tomography scans were obtained at three tertiary-care hospitals in Pakistan between January 2023 and December 2024. Bilateral acetabular diameter, depth, depth-to-diameter ratio, anatomical anteversion, inclination, lateral center-edge angle, anterior wall index and posterior wall index were measured. Sex-related differences were assessed using generalized estimating equations, while side differences were evaluated through paired analysis. Interobserver reliability was determined in 40 randomly selected scans.

Results: A total of 408 acetabula from 110 men and 94 women were evaluated. Men had significantly larger acetabular diameters and depths, whereas women demonstrated greater anteversion and inclination. Clinically relevant variation in at least one measurement was identified in 79 (38.7%) participants. Smaller anticipated acetabular cup sizes were more frequent among women, while shallow acetabula commonly occurred with increased inclination and reduced lateral coverage. Mean differences between the right and left sides were small for all principal measurements. Measurement reliability was good to excellent, with intraclass correlation coefficients ranging from 0.84 to 0.94.

Conclusion: Acetabular morphology showed considerable individual and sex-related variation. Standardized evaluation of available pelvic CT scans could support cup-size selection, component orientation and preservation of acetabular bone during total hip arthroplasty without requiring costly navigation systems.

Keywords: Acetabulum, Anatomical Variation, Computed Tomography, Total Hip Arthroplasty.

INTRODUCTION

Total hip arthroplasty (THA) has become an effective intervention for advanced hip disease, but restoration of stable joint biomechanics depends considerably on appropriate sizing and positioning of the acetabular component.[1] The acetabulum is not a uniform hemispherical cavity because its diameter, depth, inclination, version and regional wall coverage vary among individuals and populations.[2]

Computed tomography (CT) permits multiplanar evaluation of acetabular anatomy and provides more reproducible assessment of version and three-dimensional orientation than conventional pelvic radiography.[3] A CT-based study from northern India demonstrated considerable variability in acetabular depth, width, sector angles and version, indicating that measurements derived from Western populations may not be universally applicable.[4]

Research from Pakistan has also shown sex-related variation in acetabular depth and coverage, although most available local studies have relied on conventional radiographs or dry bones rather than cross-sectional imaging.[5] Three-dimensional CT analysis in Asian adults has identified differences in acetabular size and orientation that may influence implant selection, reaming and component containment.[6] Women commonly have smaller acetabular dimensions and greater anteversion than men, creating a risk of anterior overhang, posterior under coverage or inappropriate cup selection when uniform anatomical assumptions are followed.[7]

Acetabular orientation is also influenced by pelvic position, making the distinction between anatomical and functional version important when translating supine CT measurements into operative targets.[8] Incorrect cup orientation may contribute to prosthetic impingement, instability, edge loading, accelerated polyethylene wear, iliopsoas irritation and premature revision after THA.[9]

Navigation and robotic technologies can improve the reproducibility of component placement, but their purchase, maintenance and training costs restrict widespread use in low- and middle-income countries.[10] Assessment of CT examinations already obtained for clinical indications provides an economical method of developing population-specific anatomical data without additional radiation exposure or imaging expenditure.[11] Recognition of spinopelvic mobility has challenged the use of a single universal safe zone because functional acetabular orientation changes between supine, standing and sitting positions.[12] Nevertheless, native osseous morphology remains fundamental to preliminary cup-size estimation, preservation of subchondral bone and identification of patients requiring individualized surgical planning.[13] Limited CT-based information is available regarding the acetabular morphology of Pakistani adults, particularly from multicenter studies using standardized measurements.[14]

This study determined CT-based acetabular measurements in adults attending three Pakistani tertiary-care hospitals and evaluated variations according to sex, side and age, with particular emphasis on their implications for THA.

MATERIALS AND METHODS

This multicenter retrospective cross-sectional study was conducted in the anatomy, radiology and orthopedic departments of three tertiary-care hospitals across Pakistan from January 2023 to December 2024. Approval was obtained from the institutional ethics review committees before data collection. As anonymized previously acquired CT examinations were reviewed retrospectively, the requirement for individual informed consent was waived. All procedures followed the ethical principles of the Declaration of Helsinki.

Adults aged 18–75 years whose CT examinations included the entire pelvis; both acetabula and proximal femora were eligible. Scans performed for abdominal, pelvic, urological or non-hip-related clinical indications were screened consecutively. Patients with pelvic or acetabular fractures, previous hip surgery, hip arthroplasty, developmental dysplasia, advanced osteoarthritis, destructive arthropathy, femoral-head collapse, pelvic tumor, congenital deformity or poor image quality were excluded. Examinations with substantial pelvic rotation or incomplete visualization of either acetabulum were also excluded. When more than one eligible examination was available for the same patient, only the earliest scan was included.

The sample size was calculated to detect a clinically relevant difference in acetabular anteversion between men and women with 80% power and a 5% significance level. An allowance was made for correlation between bilateral measurements, incomplete imaging and missing data. The minimum required sample was 184 participants. After adding approximately 10% for potentially incomplete measurements, 204 adults were included, providing measurements from 408 acetabula.

Existing multidetector CT examinations were reviewed, and no additional imaging was performed. Scans had been obtained with participants in the supine position and lower limbs in neutral rotation. Images reconstructed at a slice thickness of 1–3 mm were accepted. Digital Imaging and Communications in Medicine data were anonymized before assessment. Multiplanar reconstruction and standard bone-window settings available on routine radiology workstations were used. The pelvis was reoriented according to the anterior pelvic plane defined by the anterior superior iliac spines and pubic tubercles.

Maximum acetabular diameter was measured between the superior and inferior acetabular margins in the plane demonstrating the largest opening. Acetabular depth was measured perpendicularly from the midpoint of the acetabular opening line to the deepest point of the acetabular fossa. The depth-to-diameter ratio was calculated by dividing acetabular depth by maximum diameter and multiplying by 100.

Anatomical anteversion was measured on the axial image passing through both femoral-head centers. It was defined as the angle between the acetabular opening line and the sagittal pelvic reference plane. Acetabular inclination was measured on the coronal plane as the angle between the opening line and the horizontal pelvic reference.

The lateral center-edge angle was measured between a vertical line passing through the femoral-head center and a line extending from the center to the lateral acetabular rim. The anterior and posterior wall indices were calculated by dividing the distance from the femoral-head center to the corresponding acetabular wall by the femoral-head radius. Operational definitions and their clinical relevance are presented in Table I.

Table I. CT Measurements and Their Relevance to Total Hip Arthroplasty

Parameter	Measurement method	Study category	Relevance to THA
Maximum diameter	Greatest acetabular opening	Small <48 mm; intermediate 48–55 mm; large >55 mm	Preliminary cup-size selection
Depth	Opening line to deepest acetabular point	Shallow <23 mm	Reaming depth and medial wall preservation
Depth-to-diameter ratio	Depth/diameter ×100	Reduced <45%	Component containment
Anatomical anteversion	Axial acetabular opening angle	<10°, 10–25° or >25°	Cup version and wall coverage
Inclination	Coronal acetabular opening angle	<35°, 35–50° or >50°	Superior coverage and edge loading
Lateral centre-edge angle	Head centre to lateral rim	<25°, 25–39° or ≥40°	Lateral femoral-head coverage
Anterior wall index	Anterior wall distance/head radius	Continuous measurement	Anterior support and cup overhang
Posterior wall index	Posterior wall distance/head radius	Continuous measurement	Posterior support and stability

Measurements were independently performed by an anatomist and an orthopaedic surgeon trained by a consultant musculoskeletal radiologist. Both observers were blinded to each other's findings. Forty examinations were randomly selected and reassessed after two weeks. The mean of the initial measurements recorded by the two observers was used in the principal analysis. Interobserver and intraobserver reliability were determined using two-way random-effects intraclass correlation coefficients.

Data were analyzed using SPSS version 26.0. Continuous variables were presented as mean and standard deviation, while categorical variables were reported as frequency and percentage. Sex differences were assessed using generalized estimating equations with participant-level clustering. Right-left differences were analyzed using paired tests. Associations with age were evaluated using multivariable regression adjusted for sex and study center. A p-value below 0.05 was considered statistically significant.

RESULTS

A total of 286 pelvic CT examinations were screened during the study period. Of these, 82 were excluded because of fractures, advanced hip degeneration, previous surgery, incomplete pelvic visualization, deformity or inadequate image quality. The final analysis included 204 participants and 408 acetabula.

The mean age of the participants was 45.7±14.1 years. There were 110 (53.9%) men and 94 (46.1%) women. The demographic and imaging characteristics of the participants are presented in Table II.

Table II. Characteristics of the Study Participants (N=204)

Characteristic	Overall	Men (n=110)	Women (n=94)

Age, years	45.7±14.1	46.5±14.0	44.8±14.2
18–39 years	71 (34.8)	36 (32.7)	35 (37.2)
40–59 years	86 (42.2)	48 (43.6)	38 (40.4)
60–75 years	47 (23.0)	26 (23.6)	21 (22.3)
Centre A	75 (36.8)	41 (37.3)	34 (36.2)
Centre B	68 (33.3)	37 (33.6)	31 (33.0)
Centre C	61 (29.9)	32 (29.1)	29 (30.9)
Slice thickness ≤1.5 mm	142 (69.6)	77 (70.0)	65 (69.1)
Slice thickness >1.5–3 mm	62 (30.4)	33 (30.0)	29 (30.9)

Values are presented as mean±SD or n (%). Percentages may not total exactly 100 because of rounding.

The overall mean acetabular diameter was 52.0±3.6 mm, while the mean depth was 25.1±2.7 mm. Men had larger and deeper acetabula than women. Women had greater mean anteversion and inclination and a smaller lateral centre-edge angle. The depth-to-diameter ratio and posterior wall index were comparable between the sexes, as shown in Table III**.**

Table III. Acetabular Measurements According To Sex (408 Hips)

Measurement	**Overall**	**Men (220 hips)**	**Women (188 hips)**	**Adjusted difference***	**p-value**
Maximum diameter, mm	52.0±3.6	54.1±2.9	49.6±2.8	4.39 (3.85–4.93)	<0.001
Depth, mm	25.1±2.7	26.2±2.5	23.8±2.3	2.29 (1.83–2.75)	<0.001
Depth-to-diameter ratio, %	48.3±4.5	48.5±4.4	48.0±4.6	0.43 (−0.44–1.30)	0.332
Anteversion, degrees	18.9±6.3	17.4±5.8	20.6±6.4	−3.14 (−4.30 to −1.98)	<0.001
Inclination, degrees	42.7±5.5	42.0±5.2	43.5±5.7	−1.42 (−2.46 to −0.38)	0.008
Lateral centre-edge angle, degrees	34.8±6.4	35.6±6.2	33.9±6.5	1.61 (0.40–2.82)	0.009
Anterior wall index	0.36±0.08	0.35±0.08	0.37±0.08	−0.02 (−0.04 to −0.01)	0.011
Posterior wall index	0.93±0.13	0.94±0.13	0.92±0.14	0.02 (−0.01–0.05)	0.194

Adjusted for age, centre and correlation between bilateral measurements; values in parentheses are 95% confidence intervals.

Clinically relevant variation in at least one acetabular measurement was present in 79 (38.7%) participants, while 27 (13.2%) had two or more variations. Smaller diameter, shallow depth, increased anteversion and reduced lateral coverage were more frequent among women. Large diameter and reduced anteversion were more frequent among men. Their distributions are presented in Table IV**.**

Table IV. Distribution of Clinically Relevant Acetabular Variations

Variation	**Overall hips, n (%)**	**Male hips, n (%)**	**Female hips, n (%)**	**p-value***
Diameter <48 mm	57 (14.0)	7 (3.2)	50 (26.6)	<0.001
Diameter >55 mm	64 (15.7)	56 (25.5)	8 (4.3)	<0.001
Depth <23 mm	70 (17.2)	21 (9.5)	49 (26.1)	<0.001
Depth-to-diameter ratio <45%	92 (22.5)	47 (21.4)	45 (23.9)	0.526
Anteversion <10°	29 (7.1)	20 (9.1)	9 (4.8)	0.087
Anteversion >25°	62 (15.2)	21 (9.5)	41 (21.8)	<0.001

Inclination >50°	34 (8.3)	13 (5.9)	21 (11.2)	0.047
Lateral centre-edge angle <25°	35 (8.6)	13 (5.9)	22 (11.7)	0.034

Differences between the right and left acetabula were small and statistically insignificant. An absolute bilateral difference in anteversion greater than 5° was found in 24 (11.8%) participants. Thus, population-level symmetry did not exclude clinically relevant asymmetry in individual patients. The paired comparisons are given in Table V**.**

Table V. Paired Comparison of Right and Left Acetabula (N=204 Pairs)

Measurement	**Right side**	**Left side**	**Mean paired difference**	**p-value**
Maximum diameter, mm	52.1±3.6	51.9±3.6	0.20	0.126
Depth, mm	25.2±2.7	25.0±2.7	0.17	0.141
Depth-to-diameter ratio, %	48.4±4.5	48.2±4.5	0.18	0.339
Anteversion, degrees	19.1±6.4	18.8±6.3	0.31	0.174
Inclination, degrees	42.8±5.5	42.6±5.5	0.22	0.263
Lateral centre-edge angle, degrees	34.7±6.4	34.9±6.3	−0.19	0.491

Female sex remained independently associated with smaller acetabular diameter and greater anteversion and inclination. Increasing age showed weak associations with anteversion and inclination but was not significantly related to diameter. No statistically significant differences remained among the study centers after adjustment. These findings are summarized in Table VI**.**

Table VI. Multivariable Associations with Selected Acetabular Measurements

Predictor	**Diameter, β (95% CI), mm**	**Anteversion, β (95% CI), degrees**	**Inclination, β (95% CI), degrees**
Female sex	−4.39 (−4.93 to −3.85)	3.14 (1.98–4.30)	1.42 (0.38–2.46)
Age per 10 years	−0.09 (−0.27–0.09)	0.47 (0.11–0.83)	0.32 (0.01–0.63)
Centre B versus Centre A	0.21 (−0.46–0.88)	−0.39 (−1.70–0.92)	0.44 (−0.73–1.61)
Centre C versus Centre A	−0.30 (−1.01–0.41)	0.63 (−0.76–2.02)	−0.37 (−1.62–0.88)

Generalized estimating equations included both hips and participant-level clustering.

Interobserver reliability was excellent for acetabular diameter, anteversion and inclination and good for depth and wall indices. Intraclass correlation coefficients were 0.94 for diameter, 0.88 for depth, 0.92 for anteversion, 0.91 for inclination, 0.89 for the lateral center-edge angle, 0.84 for the anterior wall index and 0.86 for the posterior wall index. Intraobserver coefficients ranged from 0.88 to 0.96. Fewer than 2% of measurements were missing, and complete-case analysis produced comparable findings.

DISCUSSION

The study demonstrated considerable variation in acetabular dimensions and orientation, with more than one-third of participants having at least one measurement outside the pre specified planning ranges. The larger acetabular diameter and depth observed in men agreed with previous anatomical evidence showing that male acetabula are generally larger, although proportional depth may remain comparable between the sexes. [15] ,[16]

The difference of approximately 4.5 mm in mean diameter was surgically relevant because acetabular components are commonly available in 2-mm increments, and reliance on a uniform expected size could result in excessive reaming or inadequate component containment.[17] The greater anteversion observed among women was consistent with recent CT-based studies and supported assessment of native orientation before selection of the operative cup target.[18] Excessive anteversion may reduce posterior coverage, whereas inadequate anteversion may increase anterior impingement; however, acetabular version should not be interpreted independently of femoral version and spinopelvic mechanics.[19]

Shallow acetabular depth, high inclination and reduced lateral coverage occurred together in several participants, indicating that acetabular variation frequently involved multiple dimensions rather than a single abnormal measurement. This combination may provide less superior and medial bone support after reaming, requiring careful component sizing, controlled medialization and preservation of available subchondral bone.[20]

The high frequency of acetabular diameter below 48 mm among women suggested a greater requirement for smaller cup sizes and supported maintaining an appropriately varied implant inventory. The small mean differences between the right and left sides supported cautious use of the unaffected contralateral hip during preoperative planning.[21] However, bilateral anteversion asymmetry exceeding 5° in approximately 12% of participants indicated that the opposite acetabulum should not automatically be regarded as an identical anatomical template.[21]

Standardization of CT orientation was important because pelvic rotation and tilt can alter apparent version and produce disagreement between anatomical, radiographic and functional measurements.[22] Supine CT did not completely represent functional acetabular orientation during standing and sitting, particularly among patients with spinal stiffness, sagittal imbalance or previous lumbar fusion. Patients with suspected spinopelvic abnormalities may therefore require additional standing and sitting lateral radiographs rather than assessment through supine CT alone.[23]

The absence of significant adjusted differences among the participating centres suggested that a standardized measurement protocol could produce comparable results across hospitals using different CT scanners. This was particularly relevant to resource-constrained healthcare systems because the measurements could be performed on existing CT workstations without purchasing robotic systems, optical navigation equipment or patient-specific instrumentation.[24]

Advanced technology can improve placement accuracy, but its effectiveness continues to depend on selecting an appropriate patient-specific target based on native anatomy and functional pelvic orientation. The multicenter design, inclusion of both sexes, assessment of bilateral acetabula and collaboration among anatomy, radiology and orthopedic departments strengthened the clinical relevance of the findings.

CONCLUSION

Acetabular morphology demonstrated considerable individual and sex-related variation. Men generally had larger and deeper acetabula, whereas women more frequently had smaller diameters, greater anteversion, and increased inclination and reduced lateral coverage. Although average right-left differences were small, clinically relevant asymmetry was present in some participants. Standardized measurements obtained from existing pelvic CT examinations can provide an affordable aid to cup-size selection, controlled reaming and individualized component orientation in resource-constrained hospitals. Dynamic spinopelvic assessment should be considered separately in patients at increased risk of functional malorientation.

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