

Sex- and age-specific differences in femoral head coverage and acetabular morphology among healthy subjects—derivation of normal ranges and thresholds for abnormality

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Abstract

Objective We aimed to clarify sex- and age-specific differences in three-dimensional and anatomic characteristics of femoral head coverage and acetabular morphology in healthy subjects.

Materials and Methods The study included 120 healthy subjects (57 male, 63 female), stratified into groups according to age and sex. We used computed tomography data to measure various anatomic alignment parameters describing femoral head coverage and acetabular morphology.

Results The lateral sector angle in the coronal plane, anterior sector angle in the sagittal plane, and posterior sector angles in the axial plane, which characterize femoral head coverage, did not differ significantly between males and females. However, the Sharp angle in the coronal plane and acetabular anteversion in both the sagittal and axial planes were significantly larger in females than in males. Overall, the age-specific trends were similar between male and female subjects. Specifically, for both males and females, the values for parameters of femoral head coverage were significantly lower in younger subjects (<50 years) than in older subjects (≥50 years); the only exception was the posterior sector angle among

females; regarding acetabular morphology, younger subjects showed significantly higher values for the acetabular roof obliquity and Sharp angle, but no difference between younger and older subjects was noted regarding acetabular anteversion in the sagittal or axial plane.

Conclusion Our data regarding sex- and age-specific differences and estimated normal ranges for parameters characterizing femoral head coverage and acetabular morphology among healthy subjects can be used to predict normal hip morphology.

Keywords Hip · Femoral head coverage · Acetabular morphology · Healthy · Normal range

Introduction

The dysplastic hip is characterized by progressive degenerative change in the articular cartilage because of concentration of the joint contact pressure in a small acetabulum [1, 2]. Acetabular overcoverage allows early, pathologic contact between the overcovering acetabulum and femoral head-neck junction, which can lead to prearthrotic chondrolabral damage due to dynamic stress at the level of the acetabular rim [3]. For diagnosing dysplastic hip and pincer-type femoroacetabular impingement, it is important to recognize abnormalities in the hip related to femoral head coverage and acetabular morphology.

Many reports have used plain radiography to evaluate femoral head coverage and acetabular morphology in healthy subjects [4–8]. Some described the CT-based determination of the normal ranges of mean percent femoral head coverage, although these data were obtained in a context unrelated to symptomatic hip disease [9, 10]. However, few evaluations have employed computed

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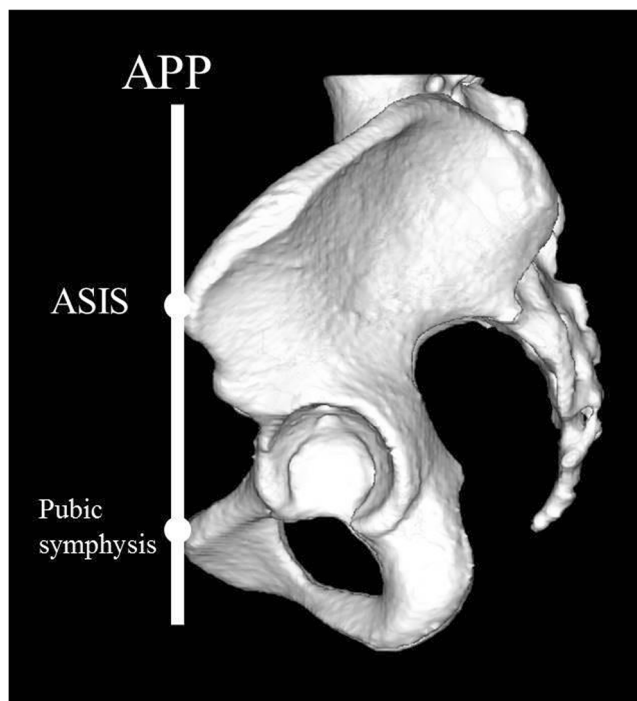


Fig. 1 Lateral view of a pelvic three-dimensional computed tomography reconstruction obtained by aligning the pelvis with the anterior pelvic plane (APP) passing through the pubic symphysis and bilateral anterior superior iliac spines

tomography (CT), which would enable determining the normal ranges for three-dimensional and anatomic parameters characterizing both femoral head coverage and acetabular morphology in healthy subjects.

The aim of the present study was to describe the range of values for three-dimensional and anatomic parameters characterizing femoral head coverage and acetabular morphology in healthy subjects as well as to identify potential sex- and age-specific differences.

Materials and methods

Subjects

This retrospective study was approved by the ethical review board at our institution.

The study enrolled healthy subjects with no hip-related symptoms (pain or limited range of motion), history of major trauma, or obvious deformity in the lower extremities (i.e., absence of radiographic findings indicating osteoarthritis, previous surgery, old fracture, or os acetabulum). The study population consisted of subjects who underwent CT evaluation related to surgical repair after anterior cruciate injury as well as subjects who underwent CT evaluation of lower leg alignment and femoral head coverage in the past [11–13]. The study population was stratified based on age (<50 vs. ≥50 years) and sex (male vs. female).

CT evaluation and measurements

CT of the pelvis and femur was performed using a SOMATOM® Sensation 16 device (Siemens, Munich, Germany) with 1-mm intervals, and multiplanar reconstruction views were obtained using CT data analysis software (3D template; Japan Medical Materials, Osaka, Japan). The anterior pelvic plane (APP) was defined as a plane passing through the pubic symphysis and the bilateral anterior superior iliac spines (ASISs) and rotated so that the ASISs were at the same level (Fig. 1) [9, 10]. The APP was then used as a reference for all measurements of rotation and translation. Specifically, the coronal plane was defined as a plane parallel to the APP. Next, the axial plane was defined as a plane perpendicular to the APP and passing through the ASISs. Finally, the sagittal plane was defined as a plane perpendicular to both the APP and the axial plane.

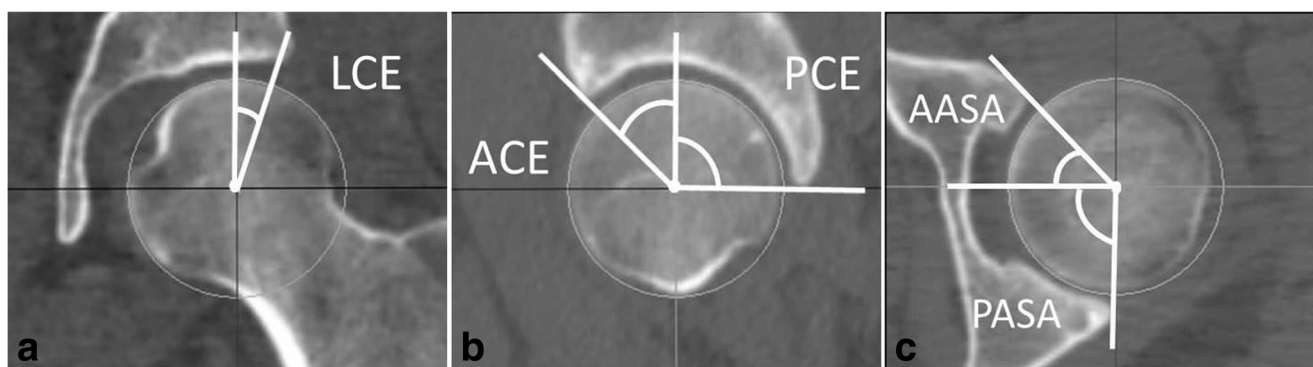


Fig. 2 Parameters of femoral head coverage. **a** Coronal view: The lateral center-edge angle (LCE) represents the angle between the vertical axis of the pelvis and a line passing through the center of the femoral head and the lateral acetabular margin. **b** Sagittal view: The anterior center-edge angle (ACE) and posterior center-edge angle (PCE) represent the angles between the vertical axis of the pelvis and a line passing through the

center of the femoral head and the anterior or posterior acetabular margin, respectively. **c** Axial view: The anterior acetabular sector angle (AASA) and posterior acetabular sector angle (PASA) represent the angles between the horizontal axis of the pelvis and a line passing through the center of the femoral head and the anterior or posterior acetabular margin, respectively

All CT-based measurements were performed by the same observer (Y.S.). Intra-observer reliability of the measurements of all parameters was assessed for a subset of 20 CT scans by blinded re-evaluation at 1 month after the first measurement and using the same technique. Inter-observer reliability was assessed by two observers (Y.S. and D.M.) independently for 20 subjects. The intra- and inter-observer reliabilities were expressed in terms of the intra-class correlation coefficient.

Femoral head coverage

Femoral head coverage was evaluated in the slice passing through the center of the femoral head (Fig. 2). The following

measurements were obtained: in the coronal plane, the lateral center-edge angle (LCE) [11, 14]; in the sagittal plane, the anterior center-edge angle (ACE) and the posterior center-edge angle (PCE) [11, 14]; in the axial plane, the anterior acetabular sector angle (AASA) [13] and the posterior acetabular sector angle (PASA) [15].

Acetabular morphology

Acetabular morphology was described in terms of the acetabular roof obliquity (ARO) [16] and Sharp angle (Sharp) [4, 17] in the coronal plane (Fig. 3) as well as the acetabular anteversion at the level of the center of the femoral head in

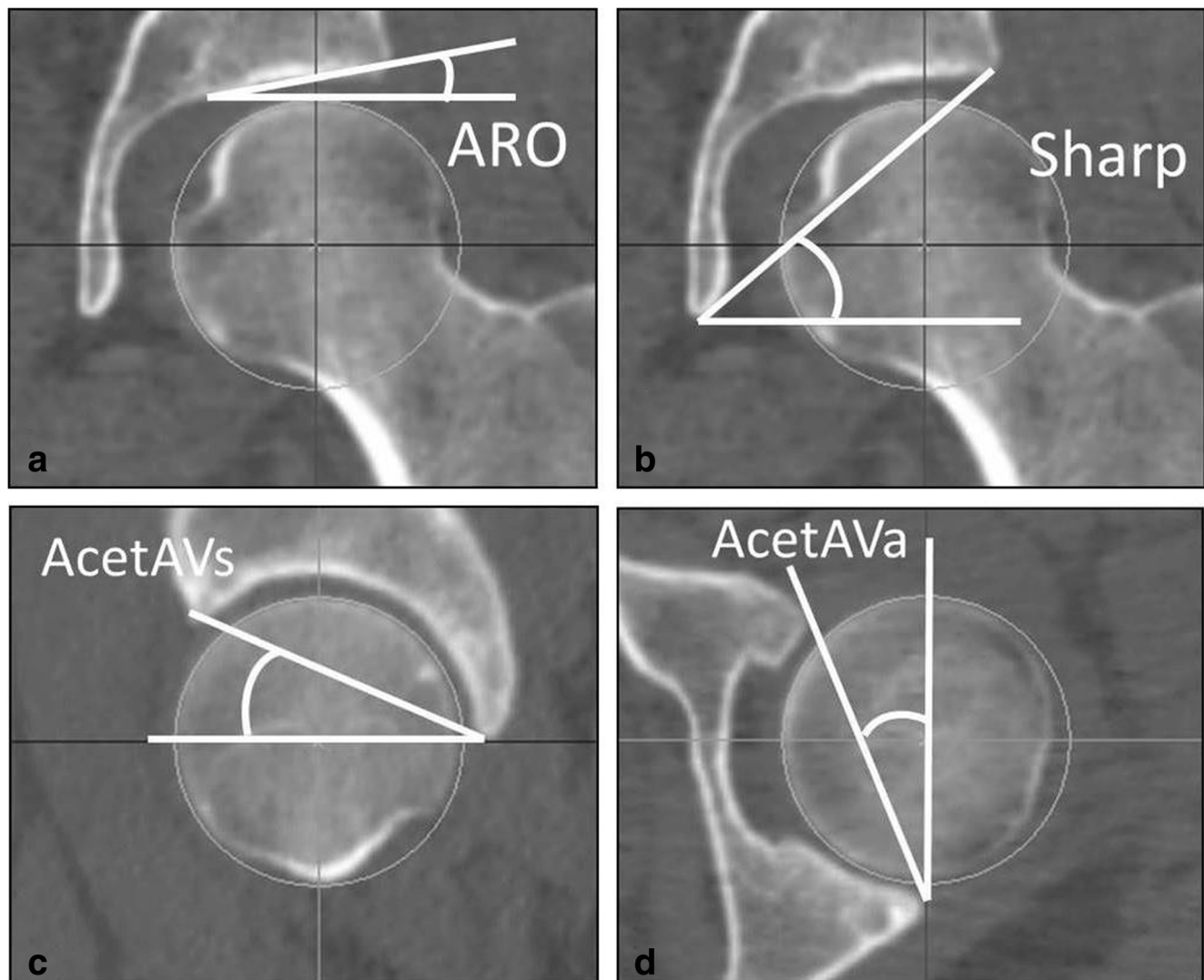


Fig. 3 Parameters of acetabular morphology. **a** Coronal view: The acetabular roof obliquity (ARO) represents the angle between the horizontal axis of the pelvis and the line that passes through the lateral margin of the acetabulum and the superior edge of the fovea. **b** Coronal view: The Sharp angle (Sharp) represents the angle between the horizontal axis of the pelvis and the line passing through the superior and inferior acetabular margins. **c** Sagittal view: The acetabular

anteversion in the sagittal plane (AcetAVs) represents the angle between the horizontal axis of the pelvis and the line passing through the anterior and posterior acetabular margins. **d** Axial view: The acetabular anteversion in the axial plane (AcetAVa) represents the angle between the vertical axis of the pelvis and the line passing through the anterior and posterior acetabular margins

the sagittal (AcetAVs) and axial planes (AcetAVa) [17]. The AcetAVs was defined as the angle between the line connecting the anterior and posterior margins of the acetabulum and a line perpendicular to the APP in the sagittal plane.

Statistical analysis

All analyses were performed using SPSS version 18 (SPSS, Chicago, IL, USA). Continuous variables were expressed in terms of mean \pm standard deviation. The distribution of values for each parameter was verified using the Shapiro-Wilk test. Mann-Whitney U-tests were used to compare the values of the parameters between male and female subjects, between younger (<50 years) and older subjects (\geq 50 years) of each sex, and between subjects who underwent repair for anterior cruciate ligament (ACL) injury and subjects who did not. Comparison of the values of the parameters between subjects who underwent repair for ACL injury and subjects was performed among younger subjects (<50 years) because all subjects with ACL repair were <50 years. For each variable, the Levene test was used to assess the equality of variances in different groups. For each analysis, P-values <0.05 were considered to indicate statistical significance.

Results

Patients

The study enrolled 120 healthy subjects (57 male, 63 female; 240 hips), of whom 17 male subjects (34 hips) and 21 female subjects (42 hips) had undergone CT evaluation related to surgical repair after ACL injury, and 82 subjects (40 male, 42 female) had undergone CT evaluation of lower leg alignment and femoral head coverage in the past [11–13]. Among

male and female subjects, the age was 44.3 ± 22.4 years (range, 11–87 years) and 44.3 ± 21.6 years (range, 11–83 years), respectively. The group of subjects younger than 50 years of age consisted of 27 males (54 hips) and 32 females (64 hips), while the group of subjects aged 50 years or older consisted of 30 males (60 hips) and 31 females (62 hips). When dividing the younger subjects according to whether or not they underwent repair for ACL injury, the Mann-Whitney U-tests indicated no significant difference in almost all parameters investigated [$P > 0.05$ for all comparisons, except for Sharp ($P = 0.023$); data not shown], suggesting that ACL injury did not affect hip morphology.

Sex-specific differences in CT parameters

Among female subjects, all CT parameters except for PCE and AcetAVs showed a normal distribution of values. On the other hand, only PCE, ARO, and AcetAVa showed a normal distribution of values among male subjects (Table 1).

The measured CT parameters were compared between male and female subjects (Table 2). Regarding femoral head coverage among male subjects, the values of parameters LCE, ACE, PCE, AASA, and PASA were $32.5^\circ \pm 7.7^\circ$, $58.2^\circ \pm 8.2^\circ$, $97.1^\circ \pm 16.2^\circ$, $61.2^\circ \pm 7.7^\circ$, and $94.5^\circ \pm 10.2^\circ$, respectively; among female subjects, these values were $31.6^\circ \pm 8.1^\circ$, $56.0^\circ \pm 10.1^\circ$, $102.9^\circ \pm 13.5^\circ$, $57.1^\circ \pm 8.3^\circ$, and $96.8^\circ \pm 8.3^\circ$, respectively. Regarding acetabular morphology among male subjects, the values of parameters ARO, Sharp, AcetAVs, and AcetAVa were $4.7^\circ \pm 6.1^\circ$, $38.6^\circ \pm 4.6^\circ$, $19.5^\circ \pm 8.5^\circ$, and $17.1^\circ \pm 5.7^\circ$, respectively; among female subjects, these values were $5.3^\circ \pm 5.9^\circ$, $40.0^\circ \pm 4.4^\circ$, $23.6^\circ \pm 9.3^\circ$, and $19.7^\circ \pm 6.1^\circ$, respectively.

For all parameters, variance was similar among male and female subjects. The values of femoral head coverage parameters LCE, ACE, and PASA did not differ significantly

Table 1 Femoral head coverage based on APP according to gender

	LCE	ACE	PCE	AASA	PASA
Male (mean)*	32.5	58.2	97.1	61.2	94.5
(SD; range)*	(7.7; 16.4 to 56.6)	(8.2;40.2 to 81.9)	(16.2; 52.8 to 135.3)	(7.7; 45 to 83.8)	(10.2; 54.9 to 127.8)
95% CI ^a	31.0 to 33.9	56.7 to 59.7	94.2 to 100.2	59.7 to 62.6	92.6 to 96.4
P value ^b	0.008	0.038	0.936	<0.001	0.008
Female (mean)*	31.6	56.0	102.9	57.1	96.8
(SD; range)*	(8.1; 11.2 to 51.1)	(10.1; 34.9 to 85.7)	(13.5; 100.5 to 105.3)	(8.3; 29.8 to 77.0)	(8.3; 72.0 to 119.6)
95% CI ^a	30.2 to 33.1	54.2 to 57.8	100.5 to 105.3	55.7 to 58.6	95.4 to 98.3
P value ^b	0.723	0.424	0.024	0.710	0.903
P value ^c	0.424	0.062	0.003	<0.001	0.053

*The values are given in degrees

^a95% confidence interval

^bStatistical test was conducted using the Shapiro-Wilk test

^cStatistical test was conducted using the nonparametric Mann-Whitney test among males and females

Table 2 Acetabular morphology based on APP according to gender

	ARO	Sharp	AcetAVs	AcetAVa
Male (mean)*	4.7	38.6	19.5	17.1
(SD; range)*	(6.1; -11.8 to 19.6)	(4.6; 26.2 to 46.8)	(8.5; 0.8 to 34.0)	(5.7; 2.2 to 33.8)
95%CI ^a	3.6 to 5.8	37.7 to 39.4	17.9 to 21.1	16.0 to 18.2
P value ^b	0.501	0.019	0.001	0.819
Female (mean)*	5.3	40.0	23.6	19.7
(SD; range)*	(5.9; -9.9 to 19.9)	(4.4; 30.8 to 51.7)	(9.3; -4.6 to 41.2)	(6.1; 1.5 to 32.1)
95% CI ^a	4.2 to 33.1	39.2 to 40.8	21.9 to 25.2	18.6 to 20.7
P value ^b	0.244	0.063	0.010	0.055
P value ^c	0.448	0.016	0.001	0.001

*The values are given in degrees

^a95% confidence interval

^bStatistical test was conducted using the Shapiro-Wilk test

^cStatistical test was conducted using the nonparametric Mann-Whitney test among males and females

between male and female subjects. However, significantly larger values were noted among female subjects for AcetAVs and AcetAVa, indicating acetabular anteversion, as well as for Sharp, indicating acetabular inclination.

Age-specific differences in CT parameters

The measured CT parameters were compared between younger (<50 years) and older (≥50 years) male subjects (Table 3). Among younger males, the values of the femoral head coverage parameters LCE, ACE, PCE, AASA, and PASA were 28.5° ± 4.4°, 54.8° ± 5.9°, 90.9° ± 15.1°, 58.8° ± 4.2°, and 90.5° ± 6.9°, respectively; among older males, these values were 36.0° ± 8.3°, 61.3° ± 8.8°, 102.8° ± 15.0°, 63.2° ± 9.4°, and 98.1° ± 11.4°, respectively. Among younger males, the values of the acetabular morphology parameters ARO, Sharp, AcetAVs, and AcetAVa were 6.7° ± 4.2°, 41.1° ± 3.2°, 18.2° ± 8.6°, and 15.9° ± 4.1°, respectively; among older males, these values were 2.8° ± 6.8°, 36.3° ± 4.4°, 20.7° ± 8.3°, and 19.0° ± 9.6°, respectively. The values of all parameters of femoral head coverage were significantly lower in younger males (<50 years) than in older males (≥50 years). Regarding acetabular morphology, the values of the parameters ARO and Sharp were significantly higher in younger males, but this was not the case for AcetAVs and AcetAVa.

The measured CT parameters were compared between younger (<50 years) and older (≥50 years) female subjects (Table 4). Among younger females, the values of the femoral head coverage parameters LCE, ACE, PCE, AASA, and PASA were 27.7° ± 7.1°, 52.0° ± 8.9°, 100.6° ± 12.8°, 55.2° ± 7.6°, and 94.6° ± 5.8°, respectively; among older females, these values were 35.7° ± 7.2°, 60.0° ± 9.6°, 105.3° ± 13.8°, 59.1° ± 8.5°, and 99.1° ± 9.7°, respectively. Among younger females, the values of the acetabular morphology parameters ARO, Sharp, AcetAVs, and AcetAVa were 7.2° ± 6.3°, 42.2°

± 4.0°, 24.5° ± 9.1°, and 19.5° ± 5.4°, respectively; among older females, these values were 3.3° ± 4.8°, 37.7° ± 3.6°, 22.6° ± 9.6°, and 19.9° ± 6.8°, respectively. The values of all parameters of femoral head coverage, except for PCE, were significantly lower in younger females (<50 years) than in older females (≥50 years). Regarding the acetabular morphology, the values of the parameters ARO and Sharp were significantly higher in younger females, but this was not the case for AcetAVs and AcetAVa. Age-specific trends among female subjects were similar to those noted for male subjects.

Reliability of measurements

The intra-class correlation coefficients for intra- and inter-observer reliability ranged from 0.98 to 0.99 and from 0.95 to 0.99, respectively, indicating excellent reliability.

Discussion

We aimed to describe the normal range of values for parameters of femoral head coverage and acetabular morphology. When considering all males included in the study, only PCE, ARO, and AcetAVa showed normal distribution of values. However, when considering only younger male subjects (aged <50 years), all parameters except for AcetAVs had a normal distribution of values. When considering all females included in the study, all parameters except for PCE and AcetAVs showed a normal distribution of values. When considering both males and females, LCE showed a normal distribution of values, with a standard deviation of approximately 8°. LCE on radiographs [3] has often been used for the diagnosis of hip dysplasia and pincer-type femoroacetabular impingement, and many reports have noted a standard deviation of <7° for LCE [15, 17, 18]. Since we observed approximately the same

Table 3 Subjects' profiles and CT parameters in males with age-specific differences

	<50	≥50	P value ^c
Subjects			
Number (hips)	27 (54)	30 (60)	
Age (years) ^a	26.2 ± 11.2	64.8 ± 11.1	<0.001
Measurements ^b (degrees)			
Femoral head coverage			
LCE	28.5 (4.4; 16.4 to 39.3)	36.0 (8.3; 19.1 to 56.6)	<0.001
95% CI	27.3–29.7	33.8–38.1	
P value ^d	0.845	0.815	
ACE	54.8 (5.9; 40.2 to 68.1)	61.3 (8.8; 44.4 to 81.9)	<0.001
95% CI	53.1–56.4	59.0–63.6	
P value ^d	0.990	0.366	
PCE	90.9 (15.1; 52.8 to 118.9)	102.8 (15.0; 63.2 to 135.3)	<0.001
95% CI	86.7–95.0	98.9–106.7	
P value ^d	0.393	0.934	
AASA	58.8 (4.2; 47.7 to 66.4)	63.2 (9.4; 45.0 to 83.8)	0.001
95% CI	57.7–60.0	60.8–65.7	
P value ^d	0.571	0.012	
PASA	90.5 (6.9; 75.0 to 103.4)	98.1 (11.4; 54.9 to 127.8)	<0.001
95%CI	88.6–92.4	95.1–101.0	
P value ^d	0.359	0.015	
Acetabular morphology			
ARO	6.7 (4.2;–5.8 to 19.6)	2.8 (6.8;–11.8 to 17.3)	<0.001
95% CI	5.6–7.9	1.1–4.6	
P value ^d	0.224	0.065	
Sharp	41.1 (3.2; 32.5 to 46.8)	36.3 (4.4; 26.2 to 46.4)	<0.001
95% CI	40.2–42.0	35.2–37.5	
P value ^d	0.214	0.542	
AcetAVs	18.2 (8.6; 0.8 to 32.4)	20.7 (8.3; 1.5 to 34.0)	0.118
95%CI	15.8–20.5	18.5–22.8	
P value ^d	0.016	0.046	
AcetAVa	15.9 (4.1; 7.0 to 23.3)	19.0 (9.6; 2.2 to 32.4)	0.027
95% CI	14.8–17.0	16.5–21.5	
P value ^d	0.222	<0.001	

^a Values are mean ± standard deviation

^b Values are mean (standard deviation; range)

^c Statistical test was conducted using the nonparametric Mann-Whitney *U* test

^d Statistical test was conducted using the Shapiro-Wilk test

standard deviation for LCE values, we considered that the selection of subjects in our sample was suitable for evaluating the normal ranges of parameters describing hip morphology. The largest variance among males and females was noted for PCE (SD: 16.2° among males, 13.5° among females), followed by PASA, suggesting that posterior coverage of the femoral head varied significantly in our study population. Regarding the morphology of the acetabulum, ARO and AcetAVa showed normal distribution of values for both males and females and may thus be useful in determining thresholds for abnormality.

With regard to sex-specific differences, LCE and ARO did not differ significantly between males and females and had similar variance. AcetAVs and AcetAVa, which indicate acetabular anteversion, were greater in females than in males, suggesting reduced anterior coverage of the acetabulum in females and increased posterior coverage in males, which supports previous reports in this direction. Larson et al. described that the anterior coverage of the acetabulum was larger in males than in females, and the posterior coverage was larger

in females than in males using a CT-based method for evaluating percent acetabular coverage of the femoral head [9]. Perreira et al. evaluated acetabular anteversion with respect to the APP in an axial slice passing through the center of the femoral head, which is similar to the approach followed in our study [19]; they found that acetabular anteversion differed significantly between males and females (18.9° ± 5.0° and 23.6° ± 5.5°, respectively). Other studies have also reported significant sex-specific differences in terms of acetabular anteversion [20–22], but the reason for these differences remains unclear. On the other hand, few reports have described AcetAVs, which represents acetabular anteversion in the sagittal plane. In our study, we chose to measure AcetAVs because the anterior acetabular edge at the level of the center of the femoral head in the axial plane does not exist in hips with a small acetabulum because the inferior edge of the tear drop lies superior to the center of the femoral head after acetabular correction via periacetabular osteotomy.

With regard to age-specific differences, all parameters of femoral head coverage, except for PCE in females, had

Table 4 Subjects' profiles and CT parameters in females with age-specific differences

	<50	≥50	P value ^c
Subjects			
Number (hips)	32 (64)	31 (62)	
Age (years) ^a	27.7 ± 11.2	65.0 ± 8.8	<0.001
Measurements ^b (degrees)			
Femoral head coverage			
LCE	27.7 (7.1; 11.2 to 43.6)	35.7 (7.2; 20.8 to 51.1)	<0.001
95% CI	25.9–29.5	33.9–37.5	
P value ^d	0.964	0.228	
ACE	52.0 (8.9; 34.9 to 75.1)	60.0 (9.6; 34.9 to 85.7)	<0.001
95% CI	49.8–54.3	57.6–62.5	
P value ^d	0.320	0.334	
PCE	100.6 (12.8; 74.0 to 124.4)	105.3 (13.8; 69.5 to 139.8)	0.053
95% CI	97.4–103.8	101.8–108.8	
P value ^d	0.038	0.171	
AASA	55.2 (7.6; 37.5 to 72.2)	59.1 (8.5; 29.8 to 77.0)	0.009
95% CI	53.3–57.1	56.9–61.2	
P value ^d	0.339	0.231	
PASA	94.6 (5.8; 74.0 to 124.4)	99.1 (9.7; 72.0 to 119.6)	0.002
95% CI	93.1–96.1	96.6–101.6	
P value ^d	0.016	0.626	
Acetabular morphology			
ARO	7.2 (6.3; -9.9 to 19.9)	3.3 (4.8; -4.6 to 18.9)	<0.001
95% CI	5.6–8.7	2.1–4.5	
P value ^d	0.229	0.041	
Sharp	42.2 (4.0; 35.1 to 51.7)	37.7 (3.6; 30.8 to 46.5)	<0.001
95% CI	41.2–43.2	36.8–38.6	
P value ^d	0.140	0.204	
AcetAVs	24.5 (9.1; 5.0 to 41.2)	22.6 (9.6; -4.6 to 39.2)	0.270
95% CI	22.2–26.7	20.2–25.6	
P value ^d	0.874	0.063	
AcetAVa	19.5 (5.4; 7.1 to 29.4)	19.9 (6.8; 1.5 to 32.1)	0.731
95% CI	18.1–20.8	18.1–21.6	
P value ^d	0.242	0.094	

^a Values are mean ± standard deviation

^b Values are mean (standard deviation; range)

^c Statistical test was conducted using the nonparametric Mann-Whitney *U* test

^d Statistical test was conducted using the Shapiro-Wilk test

significantly lower values in younger subjects (<50 years) than in older subjects (≥50 years). While this aspect has been studied only in few reports, one explanation may involve muscle weakness due to an age-related increase in joint instability, which leads to a decrease in the range of motion in the hip joint and an increase in stress at the acetabular edge, promoting osteophyte formation.

Since Wiberg described the development of osteoarthritic changes in young adults with a dysplastic hip defined as a center-edge (CE) angle of <20° on antero-posterior radiographs [3], many reports have employed a definition of the dysplastic hip based on the CE angle, because the development of osteoarthritic changes was primarily dependent on the

lateral coverage of the femoral head. Tallroth et al. measured such CT parameters, and, while the normality of the distribution was not evaluated, the normal range describing the variation of the acetabulum morphology in the normal population was determined as mean ± 2 SD [23]. The normal range of values for the CE angle indicating lateral coverage in males with a median age of 43 years (14–78 years) was 26°–52°; in females, the normal range was 29°–57°. However, age-related effects were not considered in the study of Tallroth et al. [23]. We found that all femoral head coverage parameters, except for PCE in females, had significantly lower values in younger subjects (<50 years) than in older subjects (≥50 years). ARO and Sharp indicated a large slope of the acetabulum in

younger females. Therefore, we believe that younger subjects (<50 years) should be considered when determining normal ranges.

Age-specific differences in acetabular anteversion were also evaluated. Stem et al. found that acetabular anteversion was associated with age and increased by approximately 0.7° for every 10-year increase in age [21]. Of note, their measurement was not based on anatomic alignment, but on pelvic alignment with respect to the CT table. The discrepancy between their results and the results of our study may be explained by the fact that pelvic alignment in the sagittal plane becomes tilted backward with age, and thus anatomic alignment does not coincide with pelvic alignment. Our measurements were based on anatomic alignment. We noted that the values of AcetAVs and AcetAVa did not differ among younger and older females, which was also the case for AcetAVs among males, although AcetAVa did differ between younger and older males. The standard deviation of AcetAVa in older males (≥ 50 years) was 9.6° , and this subgroup showed the highest values for acetabular anteversion, although the mean value (19.0°) of AcetAVa was similar to that noted for younger and older females.

Ito et al. used three-dimensional CT to investigate the deficiency type and degree of acetabular dysplasia among 55 subjects (50 females, 5 males; mean age, 35 years) [24]. As our subjects and their subjects were of the same race, we could compare our conclusions against theirs. Ito et al. classified acetabular dysplasia into four types according to the AASA (cutoff, 50°) and PASA (cutoff, 50°). In subjects with anterior and posterior deficiency, the mean values for AASA and PASA were 40.7° and 81.9° , respectively, which approximately coincide with the lower limits of the normal range estimated in younger females of our present study (i.e., 2 SD from the mean) for AASA (40.0°) and PASA (83.0°), respectively. In subjects with mild deficiency, AASA (55.2°) and PASA (92.4°) were very similar to the mean estimated in younger females of our present study for AASA (55.2°) and PASA (94.6°), respectively.

The present study has three main limitations. First, our sample included patients with ACL injury, which is reported to be associated with restricted hip rotation [25]. However, these patients had no obvious morphologic abnormality, and we have no report that they developed osteoarthritis of the hip during the period following the study. Second, our samples included the subjects with a LCE $<20^\circ$ or $>40^\circ$, though some previous studies mentioned that hips with CE angles $<20^\circ$ or $>40^\circ$ were excluded from the analysis. However, it is not clear whether it is appropriate to distinguish non-normal morphology based on the value of a single parameter. We believe that abnormal morphology is likely to demonstrate abnormal values in multiple parameters and that extreme values for a single parameter do not affect the statistical evaluation to a significant extent. Third, it is possible that our alignment

normalization methodology led to under- or over-reporting of variables (especially ACE, PCE, and AcetAVs) compared to values measured using a functional alignment such as the standing position. Nevertheless, we chose to carefully measure anatomic values based on the APP reference applied to CT data obtained with the subject in supine position, because pelvic alignment in the sagittal plane becomes tilted backward with age [20], and this difference in the sagittal alignment would have affected our measured values.

Conclusion

We obtained data regarding the estimated normal ranges of values for parameters characterizing femoral head coverage and acetabular morphology and quantified sex- and age-specific differences. Our results can be used to predict normal morphology.

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Compliance with ethical standards

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of our institutional and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent for undergoing the CT procedures was obtained from each subject. The requirement for informed consent for participation in the study was waived because of the retrospective nature of the study.

Conflicts of interest The authors declare that they have no conflicts of interest.

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