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CHILDREN'S ORTHOPAEDICS

Normal variation of infant hip development

PATTERNS REVEALED BY 3D ULTRASOUND

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Aims

Studies of infant hip development to date have been limited by considering only the changes in appearance of a single ultrasound slice (Graf's standard plane). We used 3D ultrasound (3DUS) to establish maturation curves of normal infant hip development, quantifying variation by age, sex, side, and anteroposterior location in the hip.

Methods

We analyzed 3DUS scans of 519 infants (mean age 64 days (6 to 111 days)) presenting at a tertiary children's hospital for suspicion of developmental dysplasia of the hip (DDH). Hips that did not require ultrasound follow-up or treatment were classified as 'typically developing'. We calculated traditional DDH indices like α angle (α_{SP}), femoral head coverage (FHC_{SP}), and several novel indices from 3DUS like the acetabular contact angle (ACA) and osculating circle radius (OCR) using custom software.

Results

α angle, FHC, and ACA indices increased and OCR decreased significantly by age in the first four months, mean α_{SP} rose from 62.2° (SD 5.7°) to 67.3° (SD 5.2°) ($p < 0.001$) in one- to eight- and nine- to 16-week-old infants, respectively. Mean α_{SP} and mean FHC_{SP} were significantly, but only slightly, lower in females than in males. There was no statistically significant difference in DDH indices observed between left and right hip. All 3DUS indices varied significantly between anterior and posterior section of the hip. Mean 3D indices of α angle and FHC were significantly lower anteriorly than posteriorly: α_{Ant} = 58.2° (SD 6.1°), α_{Post} = 63.8° (SD 6.3°) ($p < 0.001$), FHC_{Ant} = 43.0 (SD 7.4), and FHC_{Post} = 55.4° (SD 11.2°) ($p < 0.001$). Acetabular rounding measured byOCR indices was significantly greater in the anterior section of the hip ($p < 0.001$).

Conclusion

We used 3DUS to show that hip shape and normal growth pattern vary significantly between anterior and posterior regions, by magnitudes similar to age-related changes. This highlights the need for careful selection of the Graf plane during 2D ultrasound examination. Whole-joint evaluation by obtaining either 3DUS or manual 'sweep' video images provides more comprehensive DDH assessment.

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Introduction

Developmental dysplasia of the hip (DDH) occurs in between one and 50 per 1,000 live births depending on the study population, inclusion criteria, and the diagnostic methods used.[1,2] In severe cases, DDH leads to femoral head dislocation. If diagnosed within six months of birth, treatment by Pavlik harness is up to 95% effective.[3,4] But, if missed, undiagnosed DDH can lead to premature osteoarthritis and total hip arthroplasty.[5,6] Physical examinations based on Ortolani and Barlow

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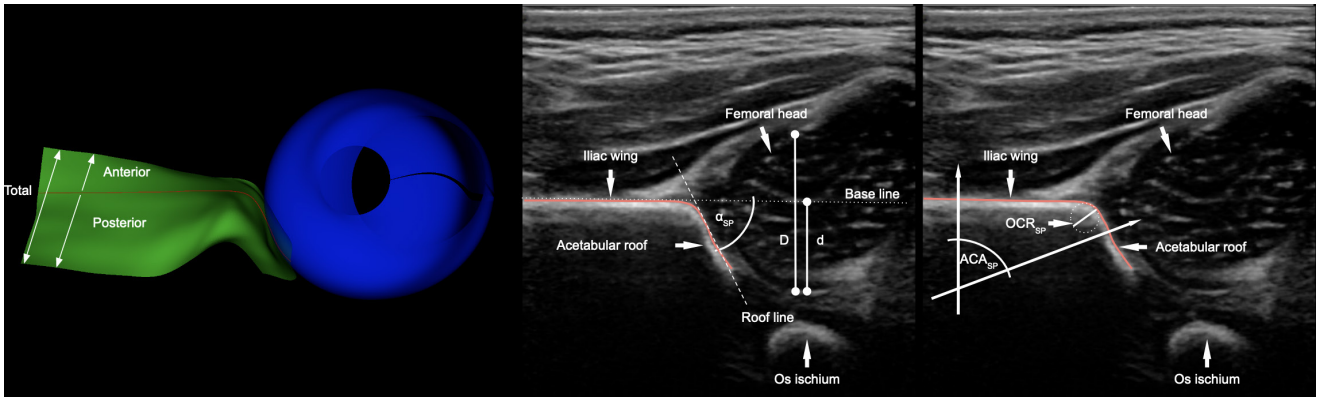

Fig. 1

Left: Acetabular surface model (ASM). Green part of the model represents iliac bone and acetabulum; blue part approximates femoral head. Standard plane contour (SPC; red) delineates the intersection of Graf's standard plane (SP) and ASM. Middle: Coronal section of 3D ultrasound scan representing manually selected Graf's SP and schema of α angle (α_{SP}) and femoral head coverage (FHC_{SP} = d/D). α_{SP} and FHC_{SP} are calculated semi-automatically from SPC (red) in a similar manner to the routine ultrasound examination. Right: ACA_{SP} is calculated from normal vectors of the SPC (red). OCR_{SP} is the largest circle fitting under SPC to approximate the roundedness of the rim.

tests lack sensitivity for mild DDH or outside the neonatal period. 2D ultrasound (2DUS) examination is widely used for DDH diagnosis, as it is more sensitive to mild cases of DDH.[7–9]

2DUS uses Graf's technique, which is based on measurement of the α angle. Graf's method categorize hips with α angle > 60° at 12 weeks as normal, < 43° as severely dysplastic.[10] Intermediate values may require follow-up ultrasound examination in 'borderline' cases to differentiate between 'immaturity' and dysplasia. Femoral head coverage (FHC) is also used in many centres to detect DDH. Index based on cartilage structure (ß angle) is also available.[11] The Graf's technique has been criticized for high interobserver variability in assessment,[12] and a high number of false positive cases requiring follow-up. Since most findings resolve spontaneously within the first few months of life, decisions on management of DDH based on ultrasound examinations tend to be subjective,[11] especially for 'borderline' cases.

These disadvantages relate to the fundamental limitations of 2DUS. Firstly, acquiring a perfect 2D image with all necessary image landmarks like straight and horizontal iliac wing, present lower limb of the ilium, labrum, os ischium, and femoral head requires extensive training and experience.[11,13] Secondly, a 2D image ignores structural variations present in anterior and posterior regions. Earlier works have shown that 3D ultrasound (3DUS) provides a better interpretation of all regions of the hip joint,[12] reduces follow-ups,[14] and is easier to acquire for novice sonographers.[13] Various 2D and 3D indices of α angle, FHC, acetabular contact angle (ACA) and osculating circle radius (OCR), have been developed to aid interpretation of 3DUS (Figure 1).[1516,17]

2D α angle and FHC indices were calculated semi-automatically from acetabular surface model in a similar manner to the Graf method and Morin and Harcke method, respectively.[11,1818] Their 3D versions extend these indices to slices with acetabulum in the 3DUS volume and report their average values. ACA uses the point normals derived from a surface model of the acetabulum to quantify the angularity of the bone. ACA is measured as the angle between the summed point normals for the iliac wing surface and acetabular roof surface.[14,16,17] Mabee et al[16] reported significantly higher reliability and slightly higher diagnostic accuracy of ACA when compared to the conventional α angle. Apart from angularity, roundness of the acetabulum is considered during hip examination in most centres. However, measures of roundedness are not well established. OCR is the radius of the circle best fitting under the apex of the acetabular curve (Figure 1) and is generally larger in more rounded (more dysplastic) hips.[14,19] While OCR indices are not independent diagnostic indices of DDH, they may supplement angularity measures (like α angle and ACA indices) to resolve cases in the 'borderline' category.

Maturation curves of the conventional 2D indices like α angle and FHC have shown a significant increase over the first four months of life.[20,21] Earlier studies also reported a higher average α angle and FHC values in males than in females.[20–22] In addition to these conventional indices (α angle and FHC) we analyzed the maturation curves of their 3D versions, as well as 2D and 3D indices of ACA and OCR in hips that did not require follow-up or treatment ("typically developing" hips). This is the first work to examine maturation of the anterior and posterior regions of the hip using 3DUS.

Methods

Clinical setting and cohort. Our retrospective analysis of prospectively collected data was approved by the University of Alberta health research ethics board. With written guardian consent, approximately two 3DUS

Table I. Traditional and novel developmental dysplasia of the hip indices. Traditional indices (with asterisk) alpha angle and femoral head coverage are calculated similarly to routine ultrasound examination. Novel indices are measured either on Graf's standard plane, across full acetabulum, or across anterior or posterior sections of the acetabulum. The border between anterior and posterior sections of the acetabulum is Graf's standard plane.

Index	2D	3D		
DDH indices	Graf's standard plane	Anterior	Posterior	Full acetabulum
α angle	α_{SP}*	α_{Ant}	α_{Post}	α_{Total}
FHC	FHC_{SP}*	FHC_{Ant}	FHC_{Post}	FHC_{Total}
ACA	ACA_{SP}	ACA_{Ant}	ACA_{Post}	ACA_{Total}
OCR	OCR_{SP}	OCR_{Ant}	OCR_{Post}	OCR_{Total}

ACA, acetabular contact angle; Ant, anterior; DDH, developmental dysplasia of the hip; FHC, femoral head coverage; OCR, osculating circle radius; Post, posterior; SP, standard plane.

scans of each hip were added to the conventional 2D static coronal imaging examination. As there is no universal screening programme in that health region, patients typically presented with risk factors for DDH (e.g. family history, breech presentation) or positive clinical examination findings (Ortolani test, Barlow test, asymmetrical thigh creases). Hips which were 1) interpreted as normal by the reporting radiologist assessment and a study team member (EO, SD, JJ), and 2) did not go on to any further management (follow-up examination or treatment) in the next six months were considered "typically developing" or "normal" and eligible for inclusion in this study. We initially extracted a total of 1,354 "normal" left hips and 1,366 "normal" right hips in infants aged ≤ 16 weeks available for analysis.

Scans not satisfying criteria set by Graf – straight and horizontal iliac wing, lower limb of the ilium, labrum, os ischium, and maximal diameter of femoral head – were excluded. We also excluded any 3D scans with more than minimal motion artifacts. As it was impractical to perform our laborious manual analysis steps on every hip in this cohort, a graduate student (EO) trained by a paediatric musculoskeletal radiologist with 17 years' experience (JJ) randomly selected up to 20 scans per side, sex, and age category. In total, we analyzed 519 infants: 273 females (mean age 62 days (6 to 111)) and 246 males (mean age 66 days (6 to 111)), 267 left hips and 252 right hips. No patient was included twice.

Ultrasound imaging. Routine 2D imaging was performed by a trained sonographer, followed by 3D imaging performed either by the same sonographer or a trained graduate student or medical student engaged in DDH research. Infants were scanned supine in the coronal plane with hip and knee joints bent to 90°. A high-resolution 13 MHz 3D linear transducer (VL13-5; Philips Healthcare, USA) was used to obtain a coronal 3DUS image of each hip, by first aligning the probe in approximately Graf's standard plane (SP), then initiating a 3.2-second automated sweep through a range of ± 15°. The resulting 3D scan comprised 256 slices (411 × 192 pixels each: 0.11 × 0.2 mm pixel size, 0.13 mm slice thickness).

Image processing. Images were processed semi-automatically by custom software written in Python (v. 3.7.7, VTK 8.1.2, USA). The reader (EO) manually selected the image slice that most closely matched the Graf's SP, and contoured approximately eight slices per scan on average identifying the lateral border of the iliac wing to acetabulum and the outline of the femoral head in all relevant 3DUS scan slices. Slices in between the manual contours were then automatically interpolated using bilinear interpolation. Smoothed acetabular and femoral head surface models were then automatically created from interpolated contours. This method has shown accuracy within 1 mm in previous assessment versus an MRI gold standard.[23] To calculate DDH indices, the hip was divided into 'anterior' and 'posterior' portions by the selected Graf's SP. Our expert radiologist (JJ) reviewed subsets of images with the reader to confirm high anatomical fidelity of the contours and appropriate Graf SP selections.

DDH indices. We semi-automatically measured conventional DDH indices (α angle and FHC) on the manually identified Graf's SP. We also measured new 2D and 3D indices developed by Hareendranathan at al,[19] Mabee et al,[16] and Zonoobi et al[14] on the slices containing acetabulum. While indices measured on the single Graf's SP slice and across whole acetabulum are referred to with subscript "SP" and "Total", respectively; indices measured across the acetabular slices located anterior and posterior to the Graf's SP use subscript "Ant" and "Post", respectively (Table I).

Statistical analysis. We tested the effect of age, sex, side, and anterior versus posterior location in the hip to variation of traditional and novel DDH indices. Sex and side were analyzed by one-way analysis of covariance (ANCOVA) testing with adjustment for age. DDH indices that did not meet one-way ANCOVA test assumptions were evaluated by independent-samples *t*-test (ISTT) and Mann-Whitney U test (MWUT) where appropriate. Differences between younger (≤ 8 weeks) and older (> 8 weeks) infants were tested by ISTT and MWUT where appropriate. Paired *t*-test and Pearson's correlation were used for differences between anterior and posterior section of the hip in 3D alpha, FHC, and ACA indices, and Wilcoxon signed-rank test and Spearman's rank-order correlation were used for 3D OCR indices. The assessments of α angle, ACA and FHC indices at two-week timepoints were performed by one-way analysis of variance (ANOVA) with post hoc Tukey analysis and Kruskall-Wallis H test was used for OCR indices. Cohen's d and $r=z/\sqrt{N}$ determined effect sizes where appropriate. All p-values < 0.05 were considered statistically significant. Statistical analyses were completed using SPSS Statistics

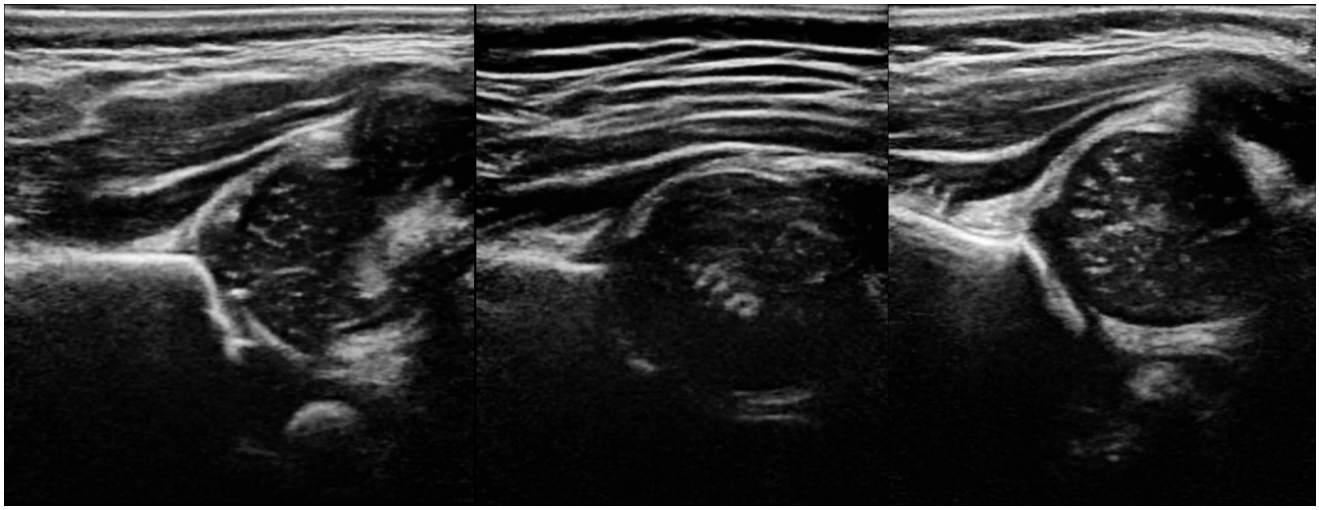

Fig. 2

Coronal slices representing examples of included (left) and excluded (middle, right) 3D hip ultrasound scans (3DUS). Left: Slice meets Graf's standard plane criteria. Middle: Os ichium is missing in all slices of 3DUS. Right: Iliac wing is not horizontal in any slice of 3DUS.

for Macintosh v. 28.0 (IBM, USA), graphs were genereated in R v. 4.2.1.

Results

Due to referral patterns following American College of Radiology guidelines indicating DDH scans should be performed at six weeks or older,[24] we had fewer infants in the youngest age groups, but allowing for this we attempted to balance each group by age and sex as much as possible. We had a total of 59 subjects aged one to four weeks out of which 11 subjects (five male, six female) were < three weeks and 48 subjects (17 male, 31 female) were between three to four weeks old. We have included scans based on Graf's criteria,[25] ideally with absence of patient motion. Examples of accepted and excluded images are provided in Figure 2.

Qualitatively, the acetabular shape showed visually obvious variation by anteroposterior location in the joint (Figure 3). In general, the anterior acetabulum is more rounded (with a larger OCR and lower α angle) than posteriorly, where a 'lip' often focally sharpens the α angle. In young infants, acetabular coverage of the femoral head is greatest near the Graf's SP and decreases anteriorly shown in Figure 4. However, we observed a steep increase of femoral head coverage posteriorly with age. We observed that newborn infants have a rounded, shallow acetabulum, which quickly becomes more sharply defined and deeper in older infants, increasing the α angle, ACA and FHC indices, and decreasing the OCR indices. These trends of index variation with age and location in the joint are shown quantitatively in Figure 4.

The increase in α_{SP} with age was substantial, and confirms findings in α angle in earlier studies. α_{SP} in males was greater than in females at all two-week timepoints (Figure 5), but increased more rapidly with age in females. Mean α_{SP} analyzed by independent-samples *t*-test increased in one to two weeks old to five to six weeks old by 8.1° in females ($p = 0.015$) and 7.1° in males ($p = 0.032$). The rate of biweekly change in mean α_{SP} in weeks < 7 and ≥ 7 was 4.1° and 1.2°, respectively, in females and 3.5° and 0.7°, respectively, in males.

Apart from $\alpha_{SP,}$ we also measured $FHC_{SP,}$ $ACA_{SP,}$ and OCR_{SP} at two-week timepoints (Figure 5). The ACA_{SP} and FHC_{SP} both increased with age similarly to the α_{SP}, while the acetabular rounding (OCR_{SP}) decreased with age after a peak at weeks three to four in females, and five to six in males.

Effects of sex, side, and age. We tested for effect of sex, side, and age on DDH indices (Table II) in 246 male and 273 female participants. The mean values of α angle, FHC, and ACA indices were significantly, although only slightly, higher for males than females ($p \leq 0.008$ for all tests), indicating sharper angularity and increased FHC. OCR_{Ant} and OCR_{Total} were higher in females, indicating greater roundedness ($p = 0.002$ and $p = 0.019$, respectively). All indices besides α_{SP} showed slightly higher values for the right hip compared to the left, but no statistically significant difference was observed. We analyzed the effect of age by grouping infants into two categories: ≤ eight weeks and > eight weeks. The differences in these groups were statistically significant in all DDH indices ($p < 0.001$ for all tests). The > eight weeks group had significantly higher α angle, FHC and ACA indices, α_{SP} (mean difference 5.1° (95% confidence interval (CI) 4.2 to 6.1); $p < 0.001$), FHC_{SP} (mean difference 4.8° (95% CI 3.7 to 5.9); $p < 0.001$), and lower OCR indices, confirming our qualitative observations of sharper angularity, improved coverage, and less rounded acetabular margins in the older infants.

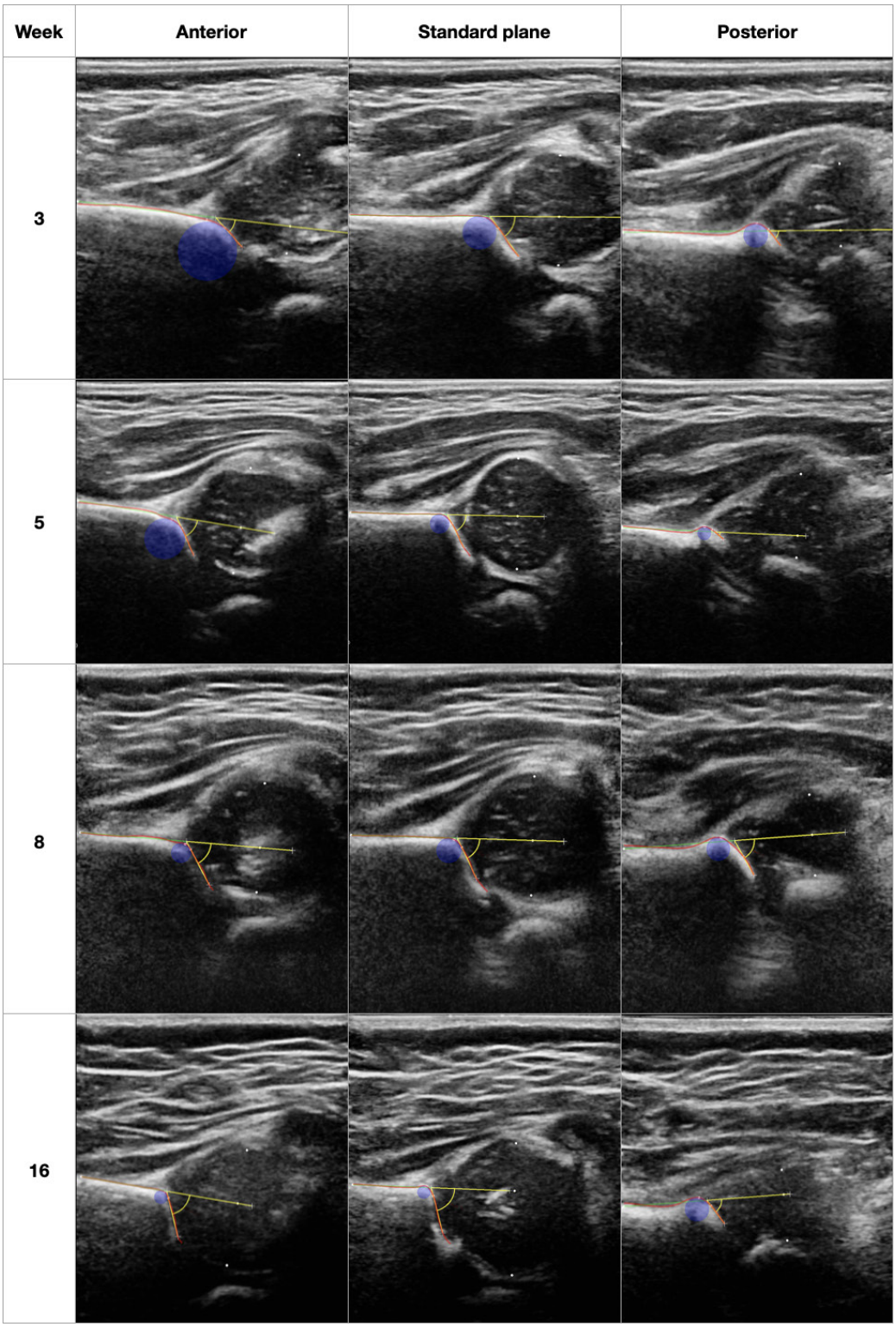

Fig. 3

Variation of hip shape by age and anteroposterior location in the joint. Typical images from 3D ultrasound scans in different female left hips at age three, five, eight, and 16 weeks (in rows) demonstrating shape of hip in Graf's standard plane (SP) as well as in anterior and posterior regions. α angle (yellow), femoral head coverage (FHC; represented by white dots), and osculating circle radius (OCR; blue circle) indices were calculated semi-automatically from countours (red). Note that the acetabulum is generally steeper in the Graf's SP than in the anterior slices, and also is perceptibly steeper in older patients than younger. In these patients: week 3: α_{SP} = 56.1°, FHC_{SP} = 44.9%, acetabular contact angle $(ACA)_{SP}$ = 54.7°, OCR_{SP} = 21.4mm; week 5: α_{SP} = 62.3°, FHC_{SP} = 47.8%, ACA_{SP} = 56.3°, OCR_{SP} = 13.5mm; week 8: α_{SP} = 63.0°, FHC_{SP} = 46.2%, ACA_{SP} = 59.3°, OCR_{SP} = 17.0mm; week 16: α_{SP} = 72.2°, FHC_{SP} = 62.3%, ACA_{SP} = 68.5°, OCR_{SP} = 9.6mm.

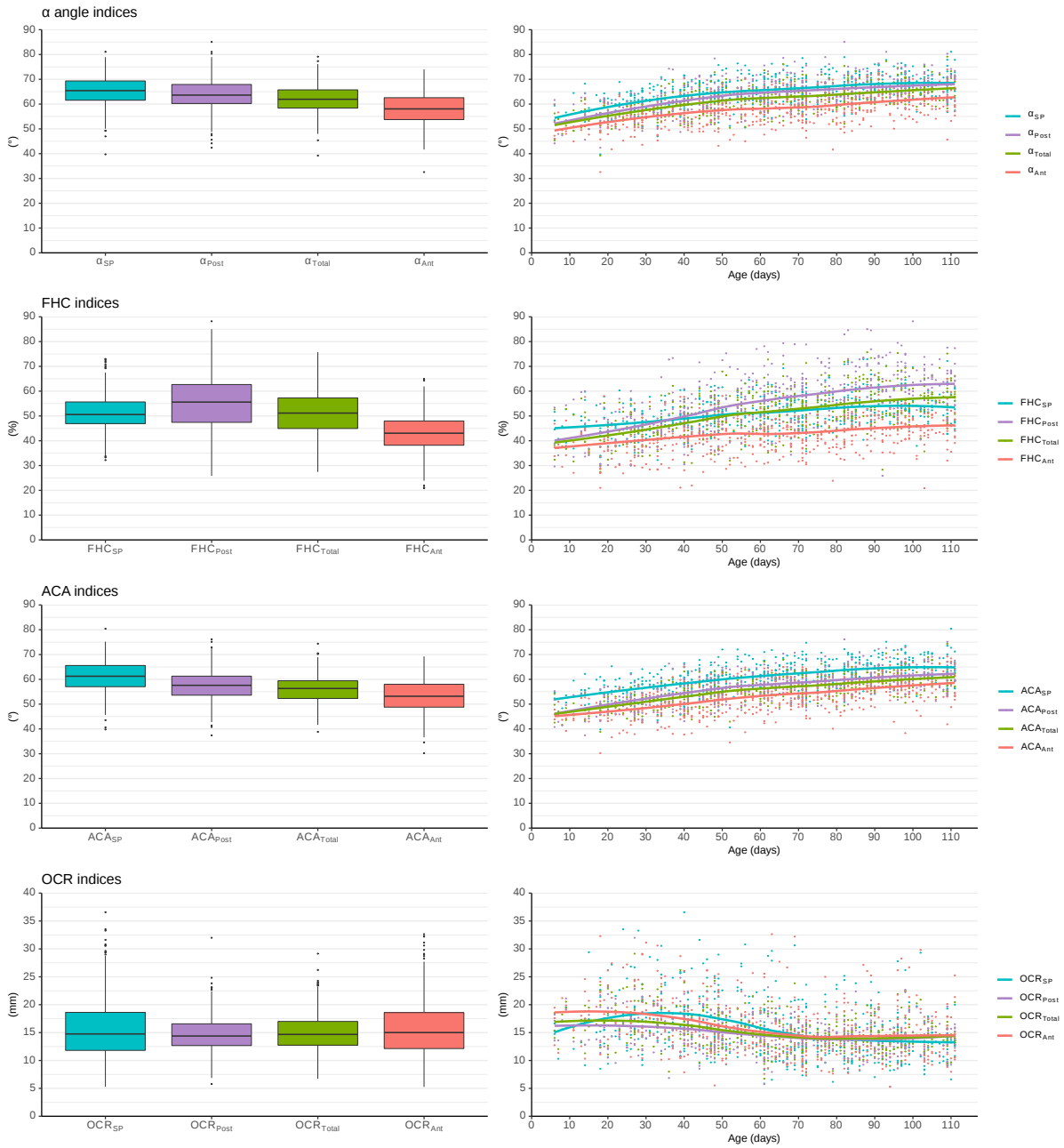

Fig. 4

Comparison of developmental dysplasia of the hip (DDH) indices: α angle, femoral head coverage (FHC), acetabular contact angle (ACA), and osculating circle radius (OCR) measured on Graf's standard plane (SP), across whole acetabulum (Total), anteriorly to SP (Ant), and posteriorly to SP (Post). Column 1: Boxplots of DDH indices. Column 2: Scatterplots of DDH indices with reference to age.

Maturation of anterior and posterior regions of the hip. Using 3DUS, we compared α angle, FHC, ACA, and OCR indices in the anterior and posterior regions of the hip (Table III). The regions were identified based on the location of the Graf's SP, which was manually identified in each image. The posterior region had significantly higher α angle, FHC, ACA, and lower OCR indices ($p < 0.001$ for all tests). Correlations of indices between anterior and posterior sections were moderate and ranged between 0.46 and 0.55. The difference in mean 3D α angle between weeks one to two and five to six trended to be slightly greater anteriorly than posteriorly in females as opposed to males (6.0°α_{Ant} and 5.4° α_{Post} in females, 6.5°α_{Ant} and 6.7° α_{Post} in males), although this was not statistically significant.

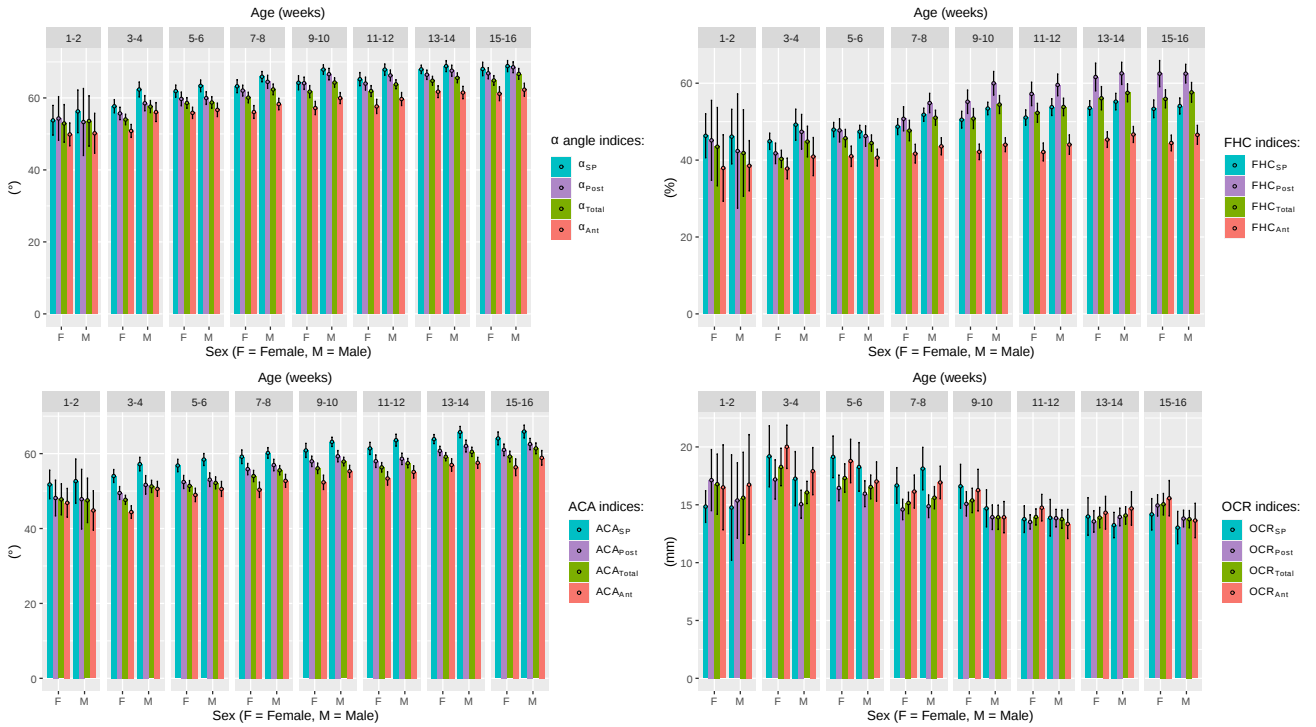

Fig. 5

Variation of developmental dysplasia of the hip (DDH) indices (α angle, femoral head coverage (FHC), acetabular contact angle (ACA) and osculating circle radius (OCR)) at two-week timepoints in male (M) and female (F) infants. Bars represent mean values, error bars represent 95% confidence intervals

Discussion

This is the first work to present normative ranges and report maturation curves for indices describing infant hip shape using 3DUS, showing significant and substantial differences in the shape of the anterior versus posterior acetabulum throughout the first four months of life.

We evaluated four 3D indices of α angle, FHC, ACA, and OCR. Conventionally, α angle and FHC are measured in clinics from a 2D coronal image as part of the hip ultrasound examination. α angle is known to increase with age, reflected in the use of Graf category IIA for 'immature' hips.[26] The unique use of 3DUS in a large patient group in this study allowed us to assess for similar variations in α angle and other parameters based on anteroposterior location in the hip. We found that variation was particularly substantial between the anterior and posterior portions of the hip. By comparing the DDH indices in anterior and posterior regions of the hip, we highlight fundamental limitations of the conventional 2DUS examination as a diagnostic test for DDH. We have used inclusion criteria based on requirements set by Graf while controlling for motion artifacts to ensure that measurements made from these images are reliable.

Confirming Graf's initial observations, studies by Tschauner et al[27] showed that the α angle increases with age and that maturation curves of α angle are significantly different between normal and dysplastic hips. Tschauner et al[27] reported that α angle in 'normal' hips showed a spurt in maturation in the first six weeks of life, and reached 60° in the second month of life and 64° at the end of third month, before the maturation curve flattens. Similar maturation curves of α angle and FHC for stable Graf I-IIb hips of age ≤ six months was reported by Cheng et al.[21] Wilkinson et al[20] similarly reported a significant increase in α angle over the first four months of life in 'normal' hips. Maturation curves of α angle and FHC reported in our study concur closely with these earlier studies overall (Figure 2).

The mean α_{SP} measured in the first two weeks category is lower than in the previous studies (53.8° (95% CI 50 to 58) in females and 56.3° (95% CI 50 to 62) in males), likely due to the small sample size in this category, and the fact that all were referred for ultrasound based on positive risk factors or previous positive clinical examination rather than as a part of a general screening programme (which does not exist in our region). The rate of change of α_{SP} was steepest at an early age, as expected.

Similar to Wilkinson et al[20] on 2DUS, we found that α_{SP} was higher in males than females across all age groups. We noted a trend toward female hips maturing faster, with more rapidly increasing α_{SP} with age. ACA and α indices are two different ways to quantify the same feature, i.e. the angularity of the acetabulum (the higher the value the sharper the angle at the acetabular roof). ACA indices

Table II. α angle, femoral head coverage, acetabular contact angle, and osculating circle radius indices according to sex, side, and age.

DDH index	Effect of sex			Effect of side			Effect of age			
	Males	Females		Left	Right		1 to 8 wks	9 to 16 wks		
α_{SP} (°)	(n = 246)	(n = 273)	p-value	(n = 267)	(n = 252)	p-value	(n = 208)	(n = 311)	Effect size	p-value
Unadjusted mean (SD)	66.7 (5.2)	64.0 (6.4)	< 0.001*	65.3 (5.7)	65.2 (6.3)	0.879*	62.2 (5.7)	67.3 (5.2)	0.948	< 0.001†
Adjusted mean[a] (95% CI)	66.5[a] (65.9 to 67.1)	64.1[a] (63.5 to 64.7)		65.2[a] (64.6 to 65.8)	65.3[a] (64.6 to 65.9)		(61.4 to 63.0)	(66.7 to 67.9)		
FHCSP **(%)**										
Unadjusted mean (SD)	52.5 (6.5)	50.0 (6.8)	< 0.001*	51.1 (6.4)	51.3 (7.1)	0.66*	48.3 (6.2)	53.1 (6.5)	0.752	< 0.001†
Adjusted mean[a] (95% CI)	52.3[a] (51.5 to 53.1)	50.2[a] (49.5 to 50.9)		51.1[a] (50.3 to 51.8)	51.3[a] (50.5 to 52.1)		(47.5 to 49.2)	(52.4 to 53.8)		
ACASP **(°)**										
Unadjusted mean (SD)	62.4 (5.5)	60.0 (6.1)	< 0.001*	60.9 (6.0)	61.3 (5.9)	0.246*	57.5 (5.3)	63.5 (5.2)	1.155	< 0.001†
Adjusted mean[a] (95% CI)	62.1[a] (61.5 to 62.8)	60.2[a] (59.6 to 60.8)		60.9[a] (60.3 to 61.5)	61.4[a] (60.8 to 62)		(56.8 to 58.2)	(62.9 to 64.1)		
Median OCR_{SP}, mm (IQR)	14.3 (11.4 to 18.3)	15.1 (12 to 19.4)	0.085‡	14.4 (12 to 19.1)	14.8 (11.6 to 18.4)	0.78‡	16.9 (13.9 to 21.5)	13.1 (10.9 to 16.7)	0.351§	< 0.001‡
αAnt **(°)**										
Unadjusted mean (SD)	59.4 (5.7)	57.2 (6.4)	< 0.001*	58.0 (5.8)	58.4 (6.5)	0.291*	55.4 (5.6)	60.1 (5.8)	0.812	< 0.001†
Adjusted mean[a] (95% CI)	59.2[a] (58.5 to 59.9)	57.4[a] (56.7 to 58)		58[a] (57.3 to 58.6)	58.5[a] (57.8 to 59.2)		(54.7 to 56.2)	(59.4 to 60.7)		
FHCAnt **(%)**										
Unadjusted mean (SD)	44.0 (7.2)	42.1 (7.4)	0.008*	42.9 (6.9)	43.1 (7.9)	0.594*	40.9 (7.7)	44.4 (6.9)	0.476	< 0.001†
Adjusted mean[a] (95% CI)	43.9[a] (43 to 44.8)	42.2[a] (41.4 to 43.1)		42.8[a] (42 to 43.7)	43.2[a] (42.3 to 44)		(39.9 to 42)	(43.6 to 45.1)		
ACAAnt **(°)**										
Unadjusted mean (SD)	54.6 (5.9)	51.9 (6.9)	< 0.001*	52.8 (6.5)	53.6 (6.7)	0.063*	49.5 (5.9)	55.7 (5.8)	1.059	< 0.001†
Adjusted mean[a] (95% CI)	54.4[a] (53.7 to 55.1)	52.1[a] (51.5 to 52.7)		52.7[a] (52.1 to 53.4)	53.7[a] (53 to 54.3)		(48.7 to 50.3)	(55 to 56.3)		
Median OCR_{Ant}, mm (IQR)	14.3 (12 to 17.6)	15.8 (12.6 to 19.3)	0.002‡	14.8 (12.2 to 18.6)	15.1 (12.1 to 18.8)	0.891‡	17.4 (14.1 to 20.7)	13.9 (11.5 to 16.9)	0.329§	< 0.001‡
αPost **(°)**										
Unadjusted mean (SD)	65.0 (6.0)	62.7 (6.3)	< 0.001*	63.7 (5.9)	63.9 (6.6)	0.517*	60.1 (6)	66.2 (5.1)	0.928	< 0.001†
Adjusted mean[a] (95% CI)	64.8[a] (64.1 to 65.4)	62.9[a] (62.3 to 63.5)		(63.0 to 64.4)	(63.1 to 64.7)	0.749†	(59.3 to 60.9)	(65.7 to 66.8)		
FHCPost **(%)**										
Unadjusted mean (SD)	57.0 (10.4)	53.9 (11.7)	0.004*	55.0 (10.7)	55.7 (11.7)	0.267*	48.3 (9.5)	60.1 (9.7)	1.216	< 0.001*
Adjusted mean[a] (95% CI)	56.6[a] (55.4 to 57.7)	54.3[a] (53.2 to 55.4)		54.9[a] (53.8 to 56)	55.8[a] (54.7 to 57)		(47.1 to 49.6)	(59 to 61.1)		
ACAPost **(°)**										
Unadjusted mean (SD)	58.2 (6.1)	56.5 (6.2)	0.003*	57.0 (5.8)	57.6 (6.5)	0.081*	53.3 (5.6)	60.0 (5.0	1.268	< 0.001†
Adjusted mean[a] (95% CI)	58.0[a] (57.3 to 58.6)	56.7[a] (56.1 to 57.3)		(56.3 to 57.7)	(56.8 to 58.4)	0.256†	(52.5 to 54.1)	(59.4 to 60.5)		
Median OCR_{Post}, mm (IQR)	14.4 (12.7 to 16.3)	14.5 (12.5 to 17.1)	0.188‡	14.5 (12.8 to 16.8)	14.3 (12.5 to 16.5)	0.104‡	15.5 (13.1 to 17.7)	13.9 (12.4 to 15.8)	0.237§	< 0.001‡

*Analysis of covariance.
†Independent-samples *t*-test.
‡Mann-Whitney U test.
§Effect size was calculated using 'r'.
ACA, acetabular contact angle; CI, confidence interval; DDH, developmental dysplasia of the hip; FHC, femoral head coverage; IQR, interquartile range; OCR, osculating circle radius; SD, standard deviation; Superscript a, Adjusted mean.

Table III. Effect of 3D indices of α angle, femoral head coverage, acetabular contact angle, and osculating circle radius on anterior and posterior regions of hip.

	Region of hip				
DDH index	**Posterior (n = 519)**	**Anterior (n = 519)**	**Correlation**	**Effect size**	**p-value**
Mean 3D α angle, ° (SD; 95% CI)	63.8 (6.3; 63.2 to 64.3)	58.2 (6.1; 57.7 to 58.8)	0.55*	0.944	< 0.001†
Mean 3D FHC, % (SD; 95% CI)	55.4 (11.2; 54.4 to 56.3)	43.0 (7.4; 42.4 to 43.6)	0.46*	1.215	< 0.001†
Mean 3D ACA, ° (SD; 95% CI)	57.3 (6.2; 56.8 to 57.9)	53.2 (6.6; 52.6 to 53.8)	0.51*	0.652	< 0.001†
Median 3D OCR, mm (IQR)	14.4 (12.7 to 16.6)	15.0 (12.1 to 18.6)	0.47‡	-0.212	< 0.001§

*Pearson's correlation.
†Paired *t*-test.
‡Spearman's rank-order correlation.
§Wilcoxon signed-rank test.
ACA, acetabular contact angle; CI, confidence interval; DDH, developmental dysplasia of the hip; FHC, femoral head coverage; IQR, interquantile range; OCR, osculating circle radius; SD, standard deviation.

were numerically smaller than α indices but all correlations and trends were similar between these two indices with the exception of the first two weeks when males had slightly lower ACA_{Total}, ACA_{Ant}, and ACA_{Post} than females.

Similar to FHC in 2D, low values of 3D FHC indices indicate increasing subluxation of the bone from the femoral head socket. We found that acetabulae were in general less rounded in males, as shown by lower values of OCR indices (i.e. smaller circles fit deep to the acetabular apex, indicating less rounding). Overall, we observed that the acetabulum in males is slightly more steeply angulated, provides slightly increased coverage of the femoral head, and is less rounded than in females, findings unsurprisingly associated with the known higher risk and prevalence of DDH seen in females.[5,7]

Generally DDH is reported to be more common in left hips,[5] likely due to the foetal position in the uterus.[5] In infants < six months of age, Wilkinson et al[20] was the only study that showed significant differences in α angles between left and right hips. As with other studies, such as by Cheng et al,[21] we found no significant difference between 'normal' left and right hips in α_{SP} and FHC_{SP}. Values of all indices besides α_{SP} were slightly higher for the right hip but no statistically significant difference was observed. The discrepant results of Wilkinson et al[20] on the significant difference between left and right side are of uncertain cause. It is worth noting that because most sonographers are right-handed, the technique for scanning right and left hips can differ, which might introduce systematic biases. As our results showed no significant difference in most DDH indices, we did not investigate this further.

Since our study was performed using 3DUS, it is the first study in which it has been possible to separately measure DDH indices at different regions of the hip bone. Confirming our strong qualitative impression, there was a significant difference between values of all DDH indices measured at the anterior versus posterior hip. The anterior acetabulum was significantly less steeply angulated, and offered significantly less coverage of the femoral head, than posteriorly. The mean anterior-posterior difference in 3D α angle was 5.6°(95% CI 5.0 to 6.1) similar magnitude to the difference of 5.2° (95% CI 4.2 to 6.1) in α_{SP} between our youngest and older infants. The effect size was highest for FHC_{Ant}vs. FHC_{Post} (Cohen's d = 1.215) and α_{Ant} versus α_{Post} (Cohen's d = 0.944). This effect size implies that the region (anterior vs posterior) used for measurement and reporting is as important as patient age in determining the value of this key index of hip dysplasia. The Graf's SP is typically identified on a slice in the middle third of the hip.We found that the more anteriorly in the hip a user locates their plane of measurement, the more likely they are to find a decreased α angle. This may explain why DDH ultrasound results in high variability in index measurements between users: if the user picks a plane a little more anterior than another user, the index value is lower. Unless the entire sweep is recorded for later review, the discrepancy cannot be resolved. This finding highlights that reliable hip ultrasound requires careful and consistent 2D slice selection. Whole-joint evaluation by routine use of cine sweeps or 3DUS is likely to be beneficial by characterizing the hip more fully than possible on single images.

When considering the possibility of combined effects, we noted that the difference in mean 3D α indices between week one to two and five to six trended greater in males than females (6.5°α_{Ant} and 6.7° α_{Post} in males and 6.0°α_{Ant} and 5.4° α_{Post} in females). This suggests maturation may occur slightly faster anteriorly than posteriorly in females, and the opposite trend can be seen in males.

This is a single-centre study, which is a limitation in that numbers may differ at other centres, but also a strength because during single-centre prospective 3DUS scanning we had the ability to control for image acquisition techniques. Our study cohort was typical of a Canadian city: ethnically diverse, but mildly Caucasian-dominant. Since we did not have detailed or validated information regarding patient ethnicity, we could not evaluate ethnic variance formally. A key limitation is that the study was not performed in a whole-population screening

setting, but rather in patients presenting with risk factors for DDH. 'Normal' hips were selected based on initial radiologist impression from 2DUS combined with an absence of further follow-up or treatment in the next six months. This does not guarantee that no dysplastic hips were present in the dataset. Only infants with risk factors were selected for this study, hence our values may be lower than a general screening population. However, determining a reliable gold standard in DDH diagnosis is challenging,[28] our patient population is a clinically relevant one since most countries do not perform universal screening, and our results were comparable to other prior studies for 2D indices. While absolute values of some indices may be slightly lower in our data than in a whole-population dataset, the trends of index variation with age, sex, and location are unlikely to be different from what has been reported. Some technical limitations exist: subjectivity of assessment whether scans satisfy Graf's SP landmarks and selection of the Graf's SP could affect our results, while our use of Gaussian filtering on surface models for the calculation of DDH indices introduced additional potential variability with changes to filtering parameters for that index. Finally, the threshold values of these indices to best differentiate between normal and dysplastic are unknown. Ideally this value needs to be determined using multicentre data accounting for inevitable variation in image acquisition protocols. As future work, we plan to expand this to a multicentre study and analyze 3D changes in dysplastic hips with respect to age, sex, side, and sagittal plane, which could potentially lead to more accurate diagnosis and treatment decisions.

The clinically optimum timeframe for DDH screening has been considered approximately six weeks, i.e. between four and eight weeks. However, in actual clinical practice, many scans are performed from birth to older ages, due to differences in time of clinical presentation. The age ranges in our study demonstrate how hips mature across the entire time during which hip ultrasound for dysplasia is technically possible. These results are not aimed at proposing the optimum hip screening timeframe.

This study highlights that ultrasound diagnosis of a 'normal' hip is far more complex than determining whether the 2D α angle is greater than 60°. In addition to the known variation of indices by age and sex, we used 3DUS to demonstrate that indices vary significantly and substantially between the anterior and posterior regions of the hip. Since indices show this much variation with location in the hip, routinely obtaining 2DUS cine sweeps of the hip, or if available, 3DUS imaging, may ultimately allow improved reliability and accuracy of ultrasound DDH diagnosis. Further study is needed to assess the impact of routine cine sweep or 3DUS imaging on long-term DDH outcomes.

In conclusion, values of ultrasound indices of hip dysplasia are dependent on age, sex, and the region of the hip being scanned. The anterior versus posterior regions of the hip show large differences in angularity, FHC, and roundedness which are not captured in conventional 2DUS-based diagnosis. These results encourage more widespread use of comprehensive evaluation of hip joints using 3DUS or anterior-to-posterior 2DUS sweeps in DDH diagnosis.

Take home message

- Assessment of hip development in infants has so far relied only on 2D ultrasound (2DUS), which does not provide a complete view of the joint.
- Various studies have shown that 3D ultrasound (3DUS) examines the hip more completely and that it is more reliable than 2DUS in diagnosing developmental dysplasia of the hip (DDH).
- This work analyzes the maturation curves for various novel DDH indices developed for 3DUS and compares these against conventional 2DUS.
- This study improves our fundamental understanding of hip development in normal infants and contrasts the growth trajectories of the anterior and posterior regions of the hip.

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