

Radiographic measurements of hip dysplasia at skeletal maturity—new reference intervals based on 2,038 19-year-old Norwegians

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Abstract

Objective Normative references for radiographic measurements commonly used in the diagnosis of developmental dysplasia of the hip at skeletal maturity are incomplete. The present study therefore aimed to establish new gender-specific standards for measurements reflecting the acetabular morphology,

namely Sharp's angle, the acetabular roof angle of Tönnis (AA) and the acetabular depth-width ratio (ADR), and measurements reflecting the position of the femoral head related to the acetabulum, namely the center-edge (CE) angle of Wiberg, the refined CE angle of Ogata, and the femoral head extrusion index (FHEI). The joint space width (JSW) is also reported.

Materials and methods The population-based 1989 Bergen Birth Cohort ($n=3,935$) was invited at age 19 years to a follow-up during 2007–09, of which 2,038 (52 %) attended. A standardized antero-posterior radiograph was assessed. The normative references are presented as mean \pm standard deviation (SD) and 2.5–97.5 percentiles with 95 % confidence intervals. **Results** A total of 2,011 (841 males, 1,170 females, mean age 18.6 (SD 0.6)) radiographs were analyzed. Sharp's angle was $38.8^{\circ} \pm 3.5^{\circ}$ in males and $40.7^{\circ} \pm 3.5^{\circ}$ in females, with 97.5 percentiles of 46° and 47° , respectively. The CE angle was $32.1^{\circ} \pm 6.1^{\circ}$ in males and $31.0^{\circ} \pm 6.1^{\circ}$ in females, with 2.5 percentiles of 21° and 20° , respectively. The FHEI was $86.0 \% \pm 6.3 \%$ in males and $85.6 \% \pm 6.6 \%$ in females, with 2.5 percentiles of 74° and 73° , respectively.

Conclusions Updated gender-specific reference ranges for radiographic measurements commonly used for hip dysplasia at skeletal maturity are reported, similar to or slightly wider than those described in the literature. Statistically significant gender differences have been confirmed for most of the measurements.

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Keywords Hip dysplasia · Adult hip · Normative references · Radiographic measurements

Introduction

Morphological abnormalities of the acetabulum and of its relationship to the femoral head are important contributing factors in developmental dysplasia of the hip (DDH) [1, 2]. They also

play an equally important role in the etiology of femoroacetabular impingement (FAI) [3–6]. Pathophysiological mechanisms involving chondral damage and subsequent labral injury of the hip joint are present in both DDH and FAI, and both conditions are assumed to be predisposing etiological factors of premature osteoarthritis of the hip (OA) [6–17]. Careful clinical examination and a standardized radiographic protocol ensuring high-quality pelvic radiographs are important in the diagnostic work-up of DDH. The adult acetabular anatomy varies according to sex, age, and ethnicity [18–22]. Furthermore, the diagnosis of DDH depends on the radiographic measurement, as well as of the cut-off values used. Several radiographic measurements are commonly used in the diagnosis of DDH (Fig. 1a–d). In the assessment of the acetabular morphology, Sharp's angle [23], the acetabular roof angle of Tönnis (AA) [1, 24], and the acetabular depth-width ratio (ADR) [8, 25] are often used. The relation between the femoral head and the acetabulum is commonly described by the center-edge (CE) angle of Wiberg [26, 27], the refined CE angle of Ogata [28], and the femoral head extrusion index (FHEI) [29]. Often, a combination of these radiographic findings is recommended in order to confirm the DDH diagnosis. The joint space width (JSW) (Fig. 2) as a discriminator of OA is also reported [30]. Existing reference values for DDH on plain radiographs at skeletal maturity are incomplete, and the present study therefore aimed to establish new gender-specific references based on a population-based cohort of 2,038 healthy 19-year-old Norwegians.

Patients and methods

Study population and design

The population-based 1989 Bergen Birth Cohort follow-up study was carried out from February 2007 to March 2009 as a long-term clinical and radiological follow-up study focusing on hip dysplasia. This study originated from a large, randomized controlled trial undertaken at this hospital in 1988–1990, designed to assess different ultrasound screening strategies in newborns [31]. A total of 4,703 subjects constituted the study base of the 1989 Bergen Birth Cohort, after exclusion of low birth weight <1,500 g ($n=34$), death within first month of life ($n=14$) and of subjects whose mother did not live in the catchment area of the hospital ($n=296$). Exclusion criteria applied before invitation at the time of follow-up were postal address outside the hospital catchment area at time of follow-up ($n=488$), emigrated or not found persons ($n=245$), and death ($n=35$). Thus, from the 1989 Bergen Birth Cohort, a total of 3,935 were invited by postal letter to participate in the follow-up (Fig. 3). A total of 2,038/3,935 (52 %) were enrolled, predominantly ethnic Norwegians. Further exclusion criteria after attendance were missing radiographs due to possible pregnancy ($n=6$) or to radiographs not obtained for other

reasons ($n=2$). Radiographs of suboptimal quality and excessive pelvic rotation as assessed by a foramen obturator index beyond range of 0.6–1.8 [1] were also excluded from the analyses ($n=19$); 102/2,011 (5.1 %) of the subjects were treated for DDH as newborns; 21/841 (2.5 %) of the males and 81/1,170 (6.9 %) of the females. The follow-up study consisted of questionnaires, clinical examination, radiographs and salivary sampling for later genetic analysis. The research protocol was approved by the medical research ethics committee of the western region of Norway, who also approved further analyses regarding the non-responders. Data on sex, age, birth weight, weight, and height (body mass index (BMI), kg/m^2) at 7 years (± 3 months) were collected from the community health care centers in Bergen and suburbs for all those born during the study period, including the non-responders. All participants gave written informed consent according to the 1964 Declaration of Helsinki. The study was conducted in accordance with the ethical standards given by the Regional Ethical Committee for Medical and Health Research. Fifteen subjects presenting with uncertain or severe clinical and/or radiographic findings related to hip, back, or pelvic pathology were immediately scheduled for a radiological follow-up consultation (KR) and/or for a consultation with a senior pediatric orthopedic surgeon (LBE) as appropriate.

Radiological examination

All radiographs were recorded in the pediatric unit of the radiology department using a low-dose digital radiography technique (Direct Digital Radiography, Digital Diagnost System, version 1.5, Philips Medical Systems, Best, The Netherlands).

Gonadal shields were offered for males. The total mean radiation dose for the two obtained radiographs together was 0.5 Gy cm^2 . One weight-bearing, anteroposterior (AP) view and one supine frog-leg view were obtained following a strictly standardized protocol, performed by one specifically trained radiographer. For the AP view, hips were kept in a neutral abduction-adduction position, toes pointing forwards [32, 33]. The radiographer ensured correct posture during the exposures. The film/focus distance was 1.2 m and centered at 2 cm proximal to the symphysis for the AP view.

Image evaluation and radiographic measurements

All radiographs were stored in the PACS (Picture Archiving Communication System) of the hospital, and retrieved as DICOM (Digital Imaging and Communications in Medicine) files and stored at a local computer. The digital measurement program "Adult DDH" (University of Iowa Hospitals and Clinics, Iowa City, IA, USA) was used to assess all the radiographic parameters on the AP view [34]. All measurement results were automatically transferred to an Excel spreadsheet

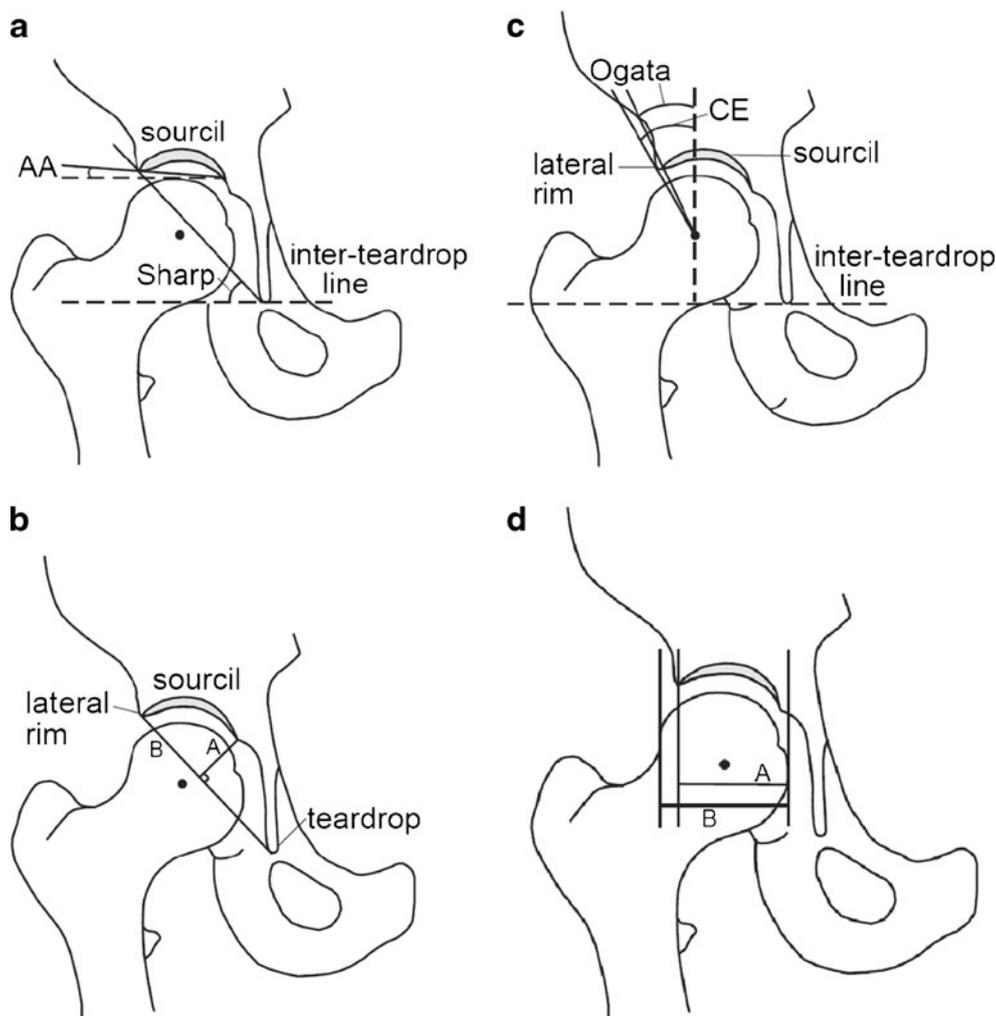


Fig. 1 **a** and **b** describe the morphology of the acetabulum: *Sharp's angle* describes the angle formed between the inter-teardrop-line and the line connecting the inferior tip of the teardrop to the lateral acetabular rim (Fig. 1a). *The acetabular roof angle of Tönnis (AA)* is the angle between a line intersecting the inferior part of the medial sourcil parallel to the inter-teardrop-line and a line running from the inferior part of the medial sourcil until the lateral acetabular rim (Fig. 1a). *The acetabular depth-width ratio (ADR)* is the depth of the acetabulum divided by the width of the acetabulum, multiplied by 1,000, presented as a ratio: $(A/B) \times 1,000$ (Fig. 1b). The width is measured from the inferior end of the teardrop to the lateral rim of the acetabulum, and the

depth is measured perpendicularly from the midpoint of the width line. **c** and **d** describe the relation between the femoral head and the acetabulum: *The CE angle of Wiberg* is formed by a vertical line through the center of the femoral head and perpendicular to the transverse axis of the pelvis (inter-teardrop-line), and a line joining the head center with the lateral rim of the acetabulum (Fig. 1c). *The refined CE angle of Ogata* uses the lateral end of the sourcil, i.e., the weight-bearing area of the acetabulum, rather than the lateral rim of the acetabulum (Fig. 1c). *The femoral head extrusion index (FHEI)* quantifies how much of the femoral head is covered by the acetabulum, i.e., lies medial to the lateral edge of the acetabulum $(A/B \times 100)$ (Fig. 1d)

[35]. The radiographs were measured by one of three of the authors (LBL, TGL, IØE). The accuracy of the digital program has been reported previously [36]. In order to perform the standardized measurements as precisely as possible, a detailed common understanding of important pelvic landmarks and of all the measurements was ensured prior to the analyses. The radiographic teardrop is a landmark seen on the AP view. Its medial surface consists of the cortical surface of the pelvis, and its lateral border consists of the cortical surface of the middle third of the acetabular fossa [37]. The inter-teardrop-line, connecting the inferior tip of both teardrops was used as the transverse axis of the pelvis. This is consistent with work

published by others [32, 38]. The most lateral point of the bony acetabulum roof is referred to as the lateral acetabular edge. In normal hips, both the posterior and the anterior acetabular rim will run downwards from the lateral edge point. The “sourcil cotyloïdien” (sourcil: French for eyebrow) represents the weight-bearing bony area of the hip joint, seen as a hyperdense arched line along the acetabular roof. In a normal hip joint, this line is horizontal or somewhat curving downward, whereas it has an upward orientation in the dysplastic hip [28]. The lateral edge of the roof can be located more laterally than the lateral point of the sourcil. Measurements of both the acetabular morphology and of the position of the femoral head

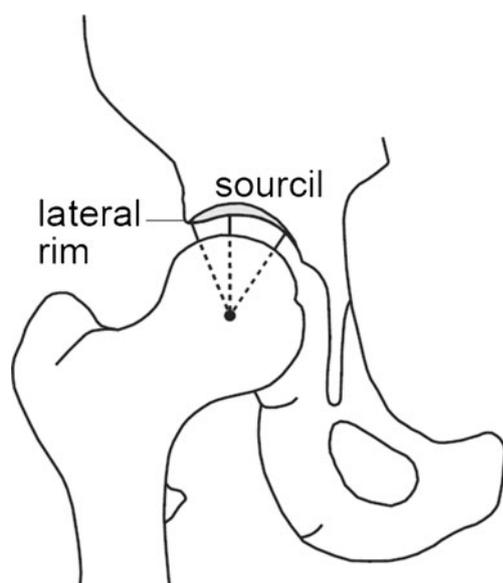


Fig. 2 The joint space width (JSW) was measured radially at three locations within the joint: namely medially (at the medial margin of the weight-bearing surface), in the middle (determined by a vertical line through the center of the femoral head), and laterally (at the lateral margin of the subchondral sclerotic line)

in the acetabulum were assessed (Fig. 1a-d). *Sharp's angle* (Fig. 1a) was originally described as “angle of inclination of the acetabulum”-“the acetabular angle” by Sharp [23]. It has occasionally been referred to as “AA” in the literature. However, “AA” is more commonly used to designate the *acetabular roof angle of Tönnis (AA)* (Fig. 1a) [1, 24]. This angle also has various synonyms, including “horizontal toit externe” (HTE) [39, 40], “acetabular roof obliquity” (ARO) [41, 42], and also “acetabular index” (AI), a term originally proposed as a measurement in children with open triradiate cartilage, where the inter-triradiate-line (Hilgenreiners line) is used instead of the inter-teardrop line [43]. In the *acetabular depth-width ratio (ADR)* (Fig. 1b), the depth was originally measured along a line running perpendicularly from the width line to the deepest point of the medial sourcil arc [8, 25]. The depth of this present study was measured slightly different to the original, corresponding to the perpendicular depth at the midpoint of the width, rather than the depth given by the deepest medial sourcil point, although they often coincide. Another depth-width ratio is also proposed in the literature, that of Heyman and Herndon from 1950 [29], using the inferiolateral point of the acetabulum rather than the teardrop tip, and the ratio is multiplied by 100 instead of by 1,000. The *center-edge (CE) angle of Wiberg* [26] (Fig. 1c) has become one of the most used parameters in the diagnosis of hip dysplasia. Wiberg initially proposed that the transverse axis be formed by an inter-center line between the two femoral heads, although the inter-teardrop line is often used for this purpose [32], including in this paper for both the CE angle and the *refined CE angle of Ogata* [28] (Fig. 1c). The *femoral*

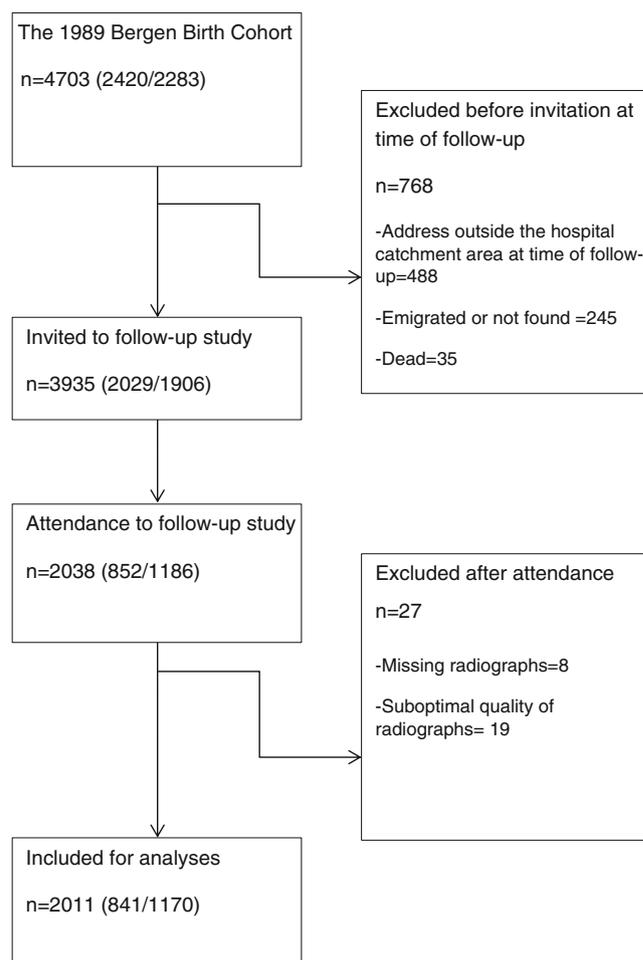


Fig. 3 Flowchart of exclusion criteria of the 1989 Bergen Birth Cohort ($n=4,703$) at follow-up

head extrusion index (FHEI) [29, 44] (Fig. 1d) is also called “femoral head coverage” or “acetabular head index” [18]. Some authors use the FHEI to describe the opposite, i.e., how much of the femoral head lies laterally to the acetabular edge [45], also termed “migration index” [32]. Measuring the *minimum joint space width (JSW)* radially is a well-accepted method for quantitative assessment of osteoarthritis (OA) [30, 46–48]. The JSW was measured at three locations, namely medially, in the middle, and laterally (Fig. 2) [49]. All three values are reported, rather than just the smallest value for each subject.

Statistics

The distribution of sex, birth weight, weight, and BMI at 7 years was compared among attenders and non-attenders to follow-up using Chi-square and *t* tests. Mean values \pm standard deviation (SD) as well as empirical 2.5 and 97.5 percentiles with their corresponding 95 % confidence intervals (CI) were calculated for both sex and sides separately for each radiographic measurement [50]. CIs were obtained using the binomial method

[51]. To take into account possible non-independence of radiological markers measured on right and left hip within each subject, repeated measures analysis of variance was used [52]. To evaluate the effects of sex and side on radiological markers, subject was considered as random term, side as within subject and sex as between subject factors. A significance level of 0.05 was decided a priori, and all the reported p values are two-tailed. No correction for multiple comparisons was performed. All calculations were performed using Stata® Statistical Software, Release 11 (StataCorp LP®, College station, TX, USA) [53].

Results

Of the 2,038/3,935 (52 %) participants who attended the follow-up, a total of 2,011 (841 males, 1,170 females) were included for further analyses (Fig. 3). Mean age was 18.6 (SD 0.6), range 17.2–20.1 years for both males and for females. The baseline characteristics of the participants compared to those that declined the follow-up invitation are reported (Table 1). A similar table has previously been reported from this study group [54]. The results for each radiographic measurement are presented (Table 2). The gender difference was statistically significant for Sharp's angle, Wiberg's CE angle, Ogata's refined CE angle (all $p < 0.0001$), and for the acetabular depth-width ratio (ADR) ($p = 0.036$), but not for the acetabular angle of Tönnis (AA) and for the femoral head extrusion index (FHEI). The side difference was statistically significant for CE, Ogata, ADR, and FHEI (all $p < 0.0001$), but not for the AA and for Sharp's angle. For the CE, Ogata, ADR, and FHEI, higher rates of values indicating dysplasia were seen in the right compared to the left hip, for both sexes. The gender-specific reference ranges based on 2.5 and 97.5 percentiles and corresponding cut-off values are reported for right and left hip, respectively (Table 3). Based on the right hip, reference ranges of Sharp's angle were 31.6–45.6° in males and 33.3–47.3° in females, with upper cut-off values of 46° and 47°, respectively. For the CE angle, reference ranges were 20.8–45.0° in males and 19.6–43.4° in females, with

lower cut-off values of 21° and 20°, respectively. The descriptive statistics of the joint space width (JSW) measured on three locations are summarized for the right and the left hip in males and females (Table 4), with lowest values for the middle position and highest values for the lateral position in both sides and for both genders. Males had statistically significant higher values in all three positions than females.

Discussion

Updated gender-specific normative references for common radiographic measurements used in the diagnosis of DDH at skeletal maturity, based on a birth cohort of 2,038 healthy 19-year-old Norwegians have been presented. Overall, similar or slightly wider reference intervals based on the appropriate 2.5/97.5 percentiles were found, as compared to cut-off values often used in the literature. The gender difference was statistically significant for all measurements except the FHEI and the AA, emphasizing the need for gender-specific ranges. All of the most common DDH radiographic measurements, including Sharp's angle, the acetabular roof angle of Tönnis (AA), the CE angle, the refined CE angle (Ogata), and the femoral head extrusion index (FHEI), except for the acetabular depth-width ratio (ADR), yielded mean values more towards the dysplastic cut-off values for females than for males. Knowledge of these reference intervals is important when interpreting radiographs performed at skeletal maturity. Values outside these percentile-based ranges are not, however, necessarily pathological, but rather values in the top or bottom 2.5 % extremities of the normal ranges. None of the results were altered significantly when similar analyses were performed excluding the 102 subjects who received treatment for DDH as newborns. Measurement values obtained in clinical practice should also be interpreted in the light of the varying intra- and inter-observer variations related to each of the measurements [36].

For Sharp's angle, the mean values of 38.8° in males and 40.7° in females are slightly higher than several of the other

Table 1 Baseline characteristics by group of attendance and non-attendance for 3,935 subjects invited to a long-term clinical and radiological follow-up

Variables	Attendance $n=2,038$	Non-attendance $n=1,897$	p value
Study 2007–09			
Boys, n (%)	852/2,038 (41.8)	1,177/1,897 (62.0)	<0.001
Girls, n (%)	1,186/2,038 (58.2)	720/1,897 (38.0)	
Birth weight (g), mean (SD)	3,529.1 (539.4)	3,520.8 (536.1)	0.630
Age (years), mean (SD)	18.6 (0.6)	NA	
BMI kg/m^2 , mean (SD)	23.1 (4.0)	NA	
Growth data available at 7 years (%)	835/2,038 (41.0)	633/1,897 (33.4)	
Boys, n (%)	363/835 (43.5)	383/633 (60.5)	<0.001
Girls, n (%)	472/835 (56.5)	250/633 (39.5)	
Weight at 7 years, mean (SD)	26.5 (4.7)	26.6 (4.8)	0.775
BMI at 7 years, mean (SD)	16.4 (2.1)	16.4 (2.1)	0.590

NA not available

Table 2 Descriptive statistics of commonly used DDH measurements in right and left hip in 841 males and 1,170 females, presented as mean \pm standard deviation (SD) and range. *p* values are related to differences between sex and side

Variable	Males		Females		P sex	P side
	Right	Left	Right	Left		
Sharp	38.8 \pm 3.5, 25.0; 49.2	38.7 \pm 3.5, 23.2; 49.1	40.7 \pm 3.5, 27.4; 51.0	40.8 \pm 3.6, 27.4; 56.2	<0.0001	0.860
AA	5.6 \pm 4.8, -11.1; 21.8	5.4 \pm 5.0, -13.0; 20.9	5.8 \pm 4.9, -13.9; 21.4	5.9 \pm 5.2, -11.1; 28.0	0.064	0.434
ADR	294.5 \pm 34.9, 193.7; 457.7	297.2 \pm 32.2, 192.5; 435.3	297.7 \pm 35.8, 165.2; 486.7	300.1 \pm 35.3, 156.3; 428.6	0.036	<0.0001
CE	32.1 \pm 6.1, 12.3; 58.5	32.8 \pm 5.8, 15.8; 52.6	30.1 \pm 6.1, 11.1; 53.1	31.4 \pm 6.0, 4.9; 54.1	<0.0001	<0.0001
Ogata	30.4 \pm 6.3, 8.2; 58.1	31.5 \pm 6.0, 15.1; 49.9	29.1 \pm 6.3, 3.7; 51.8	29.9 \pm 6.2, 4.9; 54.5	<0.0001	<0.0001
FHEI	85.6 \pm 6.3, 63.9; 108.4	86.9 \pm 6.0, 69.1; 107.5	85.6 \pm 6.6, 66.8; 113.7	86.8 \pm 6.7, 62.2; 111.4	0.372	<0.0001

Sharp Sharp's angle; *AA* acetabular roof angle of Tönnis; *ADR* acetabular depth-width ratio; *CE* center-edge angle of Wiberg; *Ogata* refined center-edge angle of Ogata; *FHEI* femoral head extrusion index

studies performed on AP radiographs [32, 55] (Table 5), and reference intervals for both males and females are slightly wider than earlier presented in the literature (Table 3). Cut-off values of $>42.3^\circ$, $\geq 43^\circ$ and $\geq 45^\circ$ have been proposed [8, 24, 56]. Sharp initially proposed a normal range of $33\text{--}38^\circ$, with $39\text{--}42^\circ$ as an upper normal limit [23]. For the AA angle of Tönnis, mean values of 5.6 and 5.8 for males and females separately are presented, with corresponding 97.5 % cut-off values of 14.8 and 15.6. Other studies report varying results with mean values ranging from around 3 to 10° [55, 57]. Tönnis supported findings by Lequesne, and proposed 10° as an approximate upper normal limit, based on extensive work on AA in children and corresponding measurements in adult hips [1, 40] (Table 3). Interestingly, the results of the present study compare better with a cut-off value of 15 found by Nakamura [56], although ethnic differences in DDH risk and pelvic configuration must be kept in mind when comparing an ethnic Norwegians with a Japanese population. Earlier published data have shown a non-negligible intra- and inter-observer variation in relation to the AA measurement [36]. As

for the ADR, mean values of 294.5 and 297.7 for males and females, respectively, were found, giving 2.5 % cut-off values of 235 and 233%. The most used cut-off value in the literature has been $<250\%$ [25]. The CE of Wiberg had mean values of 32.1 and 31.0, with corresponding cut-off values of 20.8 and 19.6 for males and females, respectively. The CE angle was originally described in 100 (50 males/50 females) healthy Swedish subjects, and reported to have a physiological range of $20\text{--}40^\circ$, with cut-off values of $<20^\circ$ indicating dysplasia, $20\text{--}25^\circ$ indicating borderline cases, and $>25^\circ$ indicating normal hips [26]. These cut-off values have been confirmed by others [8, 58–60]. The mean values of the present study compare well with other studies [55, 56, 61, 62]. The Danish study used the lateral margin of the subchondral sclerotic “sourcil” as the lateral point when measuring the CE angle, identical to the modified CE angle of Ogata, favored by Ömeroglu et al. [63]. The Danish study reported median values of 35 for both males and females, respectively. In the present study, the Ogata angle had mean values of 30.4 ± 6.3 and 29.1 ± 6.3 , with corresponding cut-off values of 18.4 and 17.1 for males and females, respectively.

Table 3 Updated gender-specific reference ranges and cut-off values (based on right hip) for DDH at skeletal maturity based on 2.5 and 97.5 percentiles with 95 % confidence intervals (CI) for each of the percentiles

Measurement	Gender	2.5 percentile (95 % CI)	97.5 percentile (95 % CI)	Confirmed or updated cut-off values	Cut-off values reported in the literature
Sharp ($^\circ$)	M	31.6 (30.6; 32.1)	45.6 (45.2; 46.3)	>46	>42.3 [24]; ≥ 43 [8]; ≥ 45 [56];
	F	33.3 (32.6; 33.9)	47.3 (46.9; 47.8)	>47	
AA ($^\circ$)	M	-4.7 (-6.5; -3.35)	14.8 (14.3; 15.6)	>15	>10 [1, 40], >15 [56]
	F	-4.1 (-4.8; -3.0)	15.6 (14.8; 16.5)	>16	
ADR (%)	M	234.6 (225.1; 237.8)	374.6 (362.1; 385.8)	<235	<250 [25]
	F	233.1 (227.4; 237.8)	370.2 (364.8; 378.8)	<233	
CE Wiberg ($^\circ$)	M	20.8 (19.9; 21.7)	45.0 (43.1; 46.0)	<21	<20 [26]
	F	19.6 (18.6; 20.5)	43.4 (42.2; 45.0)	<20	
Ogata ($^\circ$)	M	18.4 (16.4; 19.2)	42.8 (41.9; 44.2)	<18	NA
	F	17.1 (16.3; 17.7)	42.0 (41.2; 43.8)	<17	
FHEI (%)	M	73.8 (72.9; 74.8)	99.1 (97.9; 101.0)	<74	<70 [29], <75 [25]
	F	73.4 (72.3; 74.3)	100.1 (98.3; 101.7)	<73	

NA not available

Table 4 Descriptive statistics of joint space width (JSW) measurements in right and left hip in 841 males and 1,170 females, presented as mean \pm standard deviation (SD), range and 2.5–97.5 percentiles. *p* values are related to differences between sex and side

JSW (mm)	Males		Females		P sex	P side
	Right	Left	Right	Left		
Medial	4.6 \pm 1.4, 1.6; 10.9, 2.37; 7.81	4.6 \pm 1.4, 1.2; 10.0, 2.4; 7.8	4.3 \pm 1.2, 1.0; 9.8, 2.3; 7.0	4.4 \pm 1.4, 1.1; 10.3, 2.3; 7.8	<0.0001	0.138
Middle	3.8 \pm 0.9, 0.2; 6.9, 2.06; 5.60	3.7 \pm 0.9, 0.7; 6.7, 1.8; 5.5	3.6 \pm 0.8, 0.8; 6.8, 2.2; 5.2	3.5 \pm 0.8, 0.7; 7.5, 1.9; 5.1	0.0002	<0.0001
Lateral	5.6 \pm 1.13, 1.6; 11.6, 3.5; 8.0	5.5 \pm 1.1, 1.4; 9.0, 3.1; 7.8	5.3 \pm 1.1, 2.3; 9.9, 3.3; 7.5	5.2 \pm 1.1, 2.3; 9.3, 3.2; 7.5	<0.0001	<0.0001

These figures are lower than figures found in the Danish study. However, Park et al. have shown that the CE angle increases with age, and it is possible that age-related alterations in the sourcil-shaped weight bearing zone could partly explain this difference, as the Danish study group ranges from 22 to 93 years [22]. The femoral head extrusion index (FHEI) was originally presented with a normal range of 70–100 %, with an average of 90 % [29], with reference to the amount of femoral head covered by the acetabular roof. A cut-off value of 75 % was later proposed [25]. This has been supported by findings by the Danish group, presented as an inverse index, called the *lateral migration index*, with values above 25 % being indicative of dysplasia [32]. The results of the present study compare well

with previous findings [64], with cut-off values of 73.8 and 73.4 % for males and females, respectively. Overall, the findings of the present study compare well with previous findings, also in terms of sex and age.

The joint space width (JSW) is well accepted as a radiographic discriminator of hip osteoarthritis (OA) [30, 47, 48, 65]. Fredensborg originally measured JSW both vertically and horizontally radiating from the head center, and he also obtained an integral JSW, based on the average from nine measurements in the superior part of the joint. He concluded that the vertical JSW was a good measurement used alone, and that the normal value varied between 3 and 5 mm, on average slightly above 4 mm [30]. Lanyon et al. measured the JSW at

Table 5 Mean and standard deviation (SD) values for common DDH measurements on AP pelvic radiographs in males and females, compared to other studies

Radiographic measurement	Authors, year	Country, sex (M/F), age, side (R/L/R+L ^b)	Mean \pm SD, males	Mean \pm SD, females
Sharp's angle (°)	Jacobsen'05 [32]	Denmark, 1,429 M, 2,430 F 22–93 years, R	37.0 ^a \pm 3.5	39.1 ^a \pm 3.7
	Jeremic'11 [55]	Serbia, 170 M, 150 F, 21–65 years, R+L	37.5 \pm 3.6	38.5 \pm 3.9
	Laborie '12	Norway, 841 M, 1,170 F, 19 years, R	38.8 \pm 3.49	40.7 \pm 3.52
AA of Tönnis (°)	Jeremic'11 [55]	Serbia, 170 M, 150 F, 21–65 years, R+L	6.2 \pm 4.9	9.0 \pm 6.0
	Laborie '12	Norway, 841 M, 1,170 F, 19 years, R	5.64 \pm 4.8	5.84 \pm 4.9
ADR (‰)	Jacobsen'05 [32]	Denmark, 1,429 M, 2,430 F 22–93 years, R	293 ^a \pm 38	304 ^a \pm 41
	Laborie '12	Norway, 841 M, 1,170 F, 19 years, R	294.5 \pm 34.9	297.7 \pm 35.8
CE Wiberg (°)	Shi'10 [62]	China, 45 M, 55 F, 19–30 years, R+L	31.7 \pm 6.1	30.0 \pm 5.2
	Jeremic'11 [55]	Serbia, 170 M, 150 F, 21–65 years, R+L	33.6 \pm 5.8	31.3 \pm 6.9
	Laborie '12	Norway, 841 M, 1,170 F, 19 years, R	32.1 \pm 6.1	31.0 \pm 6.1
Ogata (°)	Jacobsen'05 [32]	Denmark, 1,429 M, 2,430 F, 22–93 years, R	35 ^a \pm 7.3	35 ^a \pm 7.4
	Laborie '12	Norway, 841 M, 1,170 F, 19 years, R	30.4 \pm 6.3	29.1 \pm 6.3
FHEI (%)	Jacobsen'05 [32]	Denmark, 1,429 M, 2,430 F, 22–93 years, R	12.0 ^a \pm 8.7 ^c	8.0 ^a \pm 7.8 ^c
	Aly'11 [64]	Egypt, 134 M, 110 F, 18–60 years, R+L	86.6 \pm 4.7	84.0 \pm 4.0
	Laborie '12	Norway, 841 M, 1,170 F, 19 years, R	86.0 \pm 6.3	85.6 \pm 6.6

^a Median values

^b Values based on right or left hip or both hips together

^c Percentage of uncovered portion (lateral migration index), equals the inverse FHEI value

the site of maximum narrowing and reported a mean minimum JSW of 4.1 mm in 433 males and of 3.8 mm in 598 females (both mean age 64 years) [48]. In a Turkish study by Goker et al., 17 males and 14 females (age 20–29 years) demonstrated a mean value of 3.67 ± 0.65 for the right hip, measured in the narrowest of three locations. They found that values were significantly lower in females compared to males, but no longer after adjusting for height [47]. However, the studies by Lanyon et al. and Goker et al. were performed with supine urograms and abdominal radiographs, respectively, whereas the weight-bearing AP position has been shown to be favorable in assessing hip dysplasia [66, 67]. Jacobsen et al. measured the JSW radially in three locations of the hip joint- at the lateral end of the sourcil, in the middle position corresponding to the vertical axis through the head center, and at the medial end of the sourcil [65]. They found right-sided minimal JSW values of 3.88 mm in males, and 3.91 in females. The minimal JSW represents the lowest value regardless of the three positions in the joint, and a value of ≤ 2 mm indicates OA [65]. The present study reports on values from three locations, since the aim of this study is to highlight reference values based on the two 2.5 % extremities, rather than prevalence of disease. A statistically significant difference for gender in each of the three locations was found, and a statistically significant difference for side in the middle and lateral location. Again, attention should be drawn to the clinical significance of these results, as a quite large intra- and inter-observer variation for the JSW has been previously shown [36].

To our knowledge, this is the largest population-based study addressing hip dysplasia at skeletal maturity based on all newborns delivered at the only hospital maternity unit of a well-defined area within a year. The large numbers strengthen the data. Analyses regarding non-responders show a statistically significant difference only between genders (Table 1). Contrary to other studies on hip dysplasia with wide age ranges, a well-defined age cohort additionally strengthens the study, as several of the radiographic markers are influenced by age [22, 68, 69]. The present study used a highly standardized radiographic protocol, and the radiographs were performed by one particularly trained radiographer who ensured correct posture in order to avoid pelvic tilting and rotation [70]. All radiographs were evaluated in regard to rotation. The use of a true pelvic AP radiograph also is important in the assessment of the dysplastic hip [44, 71, 72]. Several other retrospective studies are based on urograms or abdominal radiographs [73]. A weight-bearing AP view was used in the present study, given that this is the most physiological position when assessing acetabulum and related structures [19, 66, 67]. The digital measurement program was thoroughly tested and validated, and the measurements meticulously standardized before analyses [36]. Moreover, the fact that measurement results were automatically transferred to an Excel spreadsheet minimizes the risk of recording errors. Several limitations to this study are acknowledged. First, the

attendance rate of 52 % is moderate. Since all participants were included in a randomized trial evaluating the DDH screening system at birth [31], a potential selection bias has been considered. However, analyses regarding the non-responders show no substantial differences among the responders and the non-responders except for the gender distribution. Second, the pelvic tilt was not assessed in a standardized manner, but all radiographs were subjectively evaluated by a senior musculoskeletal radiologist (KR). The standardization of the radiographic examination was emphasized in order to avoid excessive tilting. Third, the ethical considerations regarding radiation of healthy young adults must be properly addressed. By using fully digital equipment and a highly standardized protocol, the total mean radiation dose for both the AP and the frog-leg view together was 0.5 Gy cm^2 . The effective dose can then be calculated using an organ-specific transforming factor, which equals 0.29 mSV/Gy cm^2 for the pelvis, yielding an effective dose of $0.5 \times 0.29 = 0.15$ mSV for both radiographs together. The effective dose in the present study without gonadal shields equals around 2 weeks of daily background radiation in Norway, given that the daily background radiation in Norway is about 0.01 mSv. In addition, gonadal shields reduced the effective dose further, up to 50–80 %. Some authors advocate the use of CT rather than conventional radiographs [74]. We believe that a conventional AP view with a minimal radiation dose following a strictly standardized protocol allows images of very high quality, and in particular allows weight-bearing images, which are recommended in the DDH assessment [44, 67]. CT imaging can only be performed in the supine position. However, we recognize the need of CT and 3D reformatting tools when planning surgical interventions in dysplastic hips [75, 76]. Last, the digital measurements were performed by one of three investigators; however, large efforts were made to standardize the measurements prior to study start. Intra- and inter-observer variation for the measurements have been shown earlier to differ to some extent, with poorer results for the measurements with lower absolute values, namely the AA and the JSW [36]. Intra- and inter-observer variation and subsequent measurement errors related to a measurement performed in a study is likely to increase further during every day clinical practice, due to more observers, less standardization of both radiographs and measurements, and a tighter time schedule.

It is important to be aware of an ongoing discussion in the literature regarding the use of the lateral edge of the bony acetabular rim or the lateral point of the weight-bearing sourcil. Many authors advocate the use of the superolateral point of the sourcil rather than the lateral edge of the bony acetabular roof when performing measurements such as Sharp's angle, acetabular angle of Tönnis, and also the CE angle of Wiberg, which then corresponds to the refined CE angle of Ogata [28, 66, 77–79]. The present study population is young and without the formation of lateral osteophytes, but this

should be kept in mind when analyzing radiographs in older age groups [73]. The radiologist should clearly state which of the two lateral points are used in order to avoid confusion.

Accurate reference values and subsequent cut-off values when assessing DDH at skeletal maturity are obviously very important in the epidemiological aspect of determining prevalences of DDH, preferably based on a combination of several of the measurements [22, 80]. However, the radiographic findings must be carefully interpreted in light of the patient's history and clinical findings, before a diagnosis of DDH can be made. As mentioned above, values outside these 2.5 % percentile-based ranges represent the more extreme values in the population, without necessarily being pathological. Furthermore, the intra- and intervariability related to the measurements should be kept in mind.

DDH has been shown to vary according to sex and ethnicity [18, 81, 82]. Neonatal hip instability (NHI) in newborns is more often seen on the left than on the right side [83, 84]. The data of the present study show that for the CE angle, Ogata, ADR, and FHEI, higher rates of values indicating dysplasia at skeletal maturity were seen in the right compared to the left hip, for both sexes.

In conclusion, updated gender-specific reference ranges for common radiographic measurements used in assessing hip dysplasia at skeletal maturity are reported, similar to or slightly wider than earlier proposed values. Statistically significant gender differences are confirmed for most of the measurements, with a tendency of more dysplastic values in females.

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

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