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SYMPOSIUM: SEX DIFFERENCES IN MUSCULOSKELETAL DISEASE AND SCIENCE

Sex Differences in Cartilage Topography and Orientation of the Developing Acetabulum: Implications for Hip Preservation Surgery

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Abstract

Background Increased attention is being placed on hip preservation surgery in the early adolescent. An understanding of three-dimensional (3-D) acetabular development as children approach maturity is essential. Changes in acetabular orientation and cartilage topography have not previously been quantified as the adolescent acetabulum completes development.

Questions/purposes We used a novel 3-D CT analysis of acetabular development in children and adolescents to determine (1) if there were sex-specific differences in the growth rate or surface area of the acetabular articular cartilage; (2) if there were sex-specific differences in acetabular version or tilt; and (3) whether the amount of version and tilt present correlated with acetabular coverage.

Methods We assessed acetabular morphology in 157 patients (314 hips); 71 patients were male and 86 were female. Patient ages ranged from 8 years to 17 years. A 3-D surface reconstruction of each pelvis was created from CT data using MIMICs software. Custom MATLAB software was used to obtain data from the 3-D reconstructions. We calculated articular surface area, acetabular version, and acetabular tilt as well as novel measurements of acetabular morphology, which we termed "coverage angles." These were measured in a radial fashion in all regions of the acetabulum. Data were organized into three age groups: 8 to 10 years old, 10 to 13 years old, and 13 to 17 years old.

Results Male patients had less acetabular anteversion in all three age groups, including at maturity (7° versus 13°, $p < 0.001$; 10° versus 17°, $p < 0.001$; 14° versus 20°, $p < 0.001$). Males had less acetabular tilt in all three age groups (32° versus 34°, $p = 0.03$; 34° versus 38°, $p < 0.001$; 39° versus 41°, $p = 0.023$). Increases in anteversion correlated with increased posterior coverage angles ($r = 0.805$; $p < 0.001$). Increases in tilt were correlated with increases in superior coverage angles ($r = 0.797$; $p < 0.001$). The posterosuperior regions of the acetabulum were the last to develop and this process occurred earlier in females compared with males. Articular surface area increased from 18 (8–10 years) to 24 mm^2 (13–17 years) in males and from 17 (8–10 years) to 21 mm^2 (13–17 years) in females. Articular surface area was higher in males beginning in the 10- to 13-year-old age group ($p = 0.001$).

Conclusions Using a novel technique to analyze acetabular morphology, we found that acetabular development occurs earlier in females than males. The posterosuperior

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region of the acetabulum is the final region to develop. The articular cartilage surface area and articular cartilage coverage of the femoral head are increasing in addition to total coverage of the femoral head during the final stages of acetabular development.

Level of Evidence Level III, prognostic study.

Introduction

An understanding of normal development of the acetabulum is essential for surgeons treating hip conditions in the child or adolescent, including pediatric orthopaedic surgeons, hip preservation specialists, and orthopaedic traumatologists. This knowledge is important for understanding the natural history of pediatric hip conditions, subsequent adult hip deformity, and the implications of surgical intervention at different stages of development.

The development of the acetabulum is extremely complex (Video Supplement 1 [Supplemental materials are available with the online version of CORR®.]) and our knowledge is incomplete. Prior histologic studies have described the complexity of the acetabulum at the cellular level [12, 13]. Multiple studies have described the development of the bony acetabulum throughout childhood and adolescence using radiographs and two-dimensional cuts from CT scans [2, 5, 9, 17]. MRI studies have described the development of the acetabular labrum [7], the appearance of secondary ossification centers of the ilium and pubis [19], and have recently characterized the irregular ossification pattern of the posterior wall/ischial secondary ossification center [4]. Little is known about the development of the articular surface. No studies have quantified how much the acetabulum grows near maturity or the articular cartilage coverage of the femoral head to our knowledge.

The lateral portion of the acetabulum is cup-shaped and composed of both hyaline cartilage and articular cartilage. This has also been termed the acetabular ring apophysis and contributes to the deepening of the acetabulum through appositional growth under the perichondrium at the lateral margin [12]. The lateral cup-shaped hyaline portion of the acetabulum is analogous to the epiphyses of the pubis, ilium, and ischium. During late childhood and adolescence, secondary ossification centers arise within the hyaline cartilage structure that herald the beginning of acetabular wall ossification. Each ossification center forms within the epiphysis of a respective innominate bone (pubis: os acetabuli, ilium: acetabular epiphysis, ischium: unnamed irregular ossification center of the posterior wall) [4, 12, 19]. These ossification centers eventually coalesce to form the bony walls of the acetabulum. The epiphyseal-equivalent, lateral-based, hyaline cartilage is lined on its concave periphery with articular cartilage that forms the articular surface of the hip. Little is known about the development of the articular surface.

We sought to characterize the normal development of the acetabulum using a novel three-dimensional (3-D) radial sequencing technique using CT scans. We specifically asked (1) if there were sex-specific differences in the growth rate or surface area of the acetabular articular cartilage; (2) if there were sex-specific differences in acetabular version or tilt; and (3) whether the amount of version and tilt present correlated with acetabular coverage.

Materials and Methods

After institutional review board approval, we performed a retrospective review on data obtained from abdominal CT scans of patients between ages 8 and 17 years in our emergency department between November 2011 and January 2012. The most common indications were to rule out appendicitis or part of a trauma workup. Patients with orthopaedic trauma were excluded. A review of the medical record was performed for each patient. Patients with orthopaedic hip conditions or neuromuscular conditions were also excluded from our review.

Using a previously validated method, 0.6-mm pelvis cuts were isolated and used to create a virtual 3-D CT model as previously described by our institution [1, 11]. Pelvises were reoriented accounting for tilt and rotation through methods previously described. A surface reconstruction of the pelvis was created using MIMICS software (Materialise, Leuven, Belgium). Pelvis models were exported using stereolithography CAD format (STL) to MATLAB (Mathworks, Natick, MA, USA) for analysis.

Custom MATLAB software was developed to automatically identify acetabulum surfaces on the pelvic models (Video Supplement 2 [Supplemental materials are available with the online version of CORR®.]). Each acetabulum was fitted with a sphere using least-squares regression. Pelvises were rotated, first in the axial plane, then in the coronal plane, so that the centers of the left and right spheres were aligned on the left-right axis. Cotyloid fossa/articular surface boundaries were traced using a custom MATLAB interface (performed by JBP and JD) (Fig. 1).

The surface areas of the acetabular articular surface and cotyloid fossa were recorded. Acetabular direction vectors were calculated by integrating surface normal vectors over the entirety of each acetabulum. The vectors were used to calculate acetabular tilt (the angle between the acetabular direction vector and the left-right axis when projected into

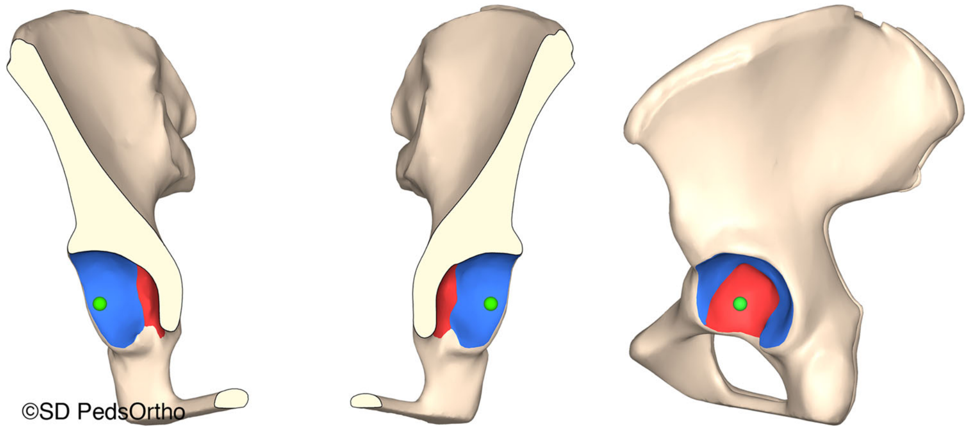

Fig. 1 A cross-sectional AP and a lateral 3-D surface reconstruction of the pelvis are shown. The cotyloid fossa was delineated from the articular surface of the acetabulum. *Red* cotyloid fossa; *blue* articular surface; *green* center-of-best-fit sphere within acetabulum.

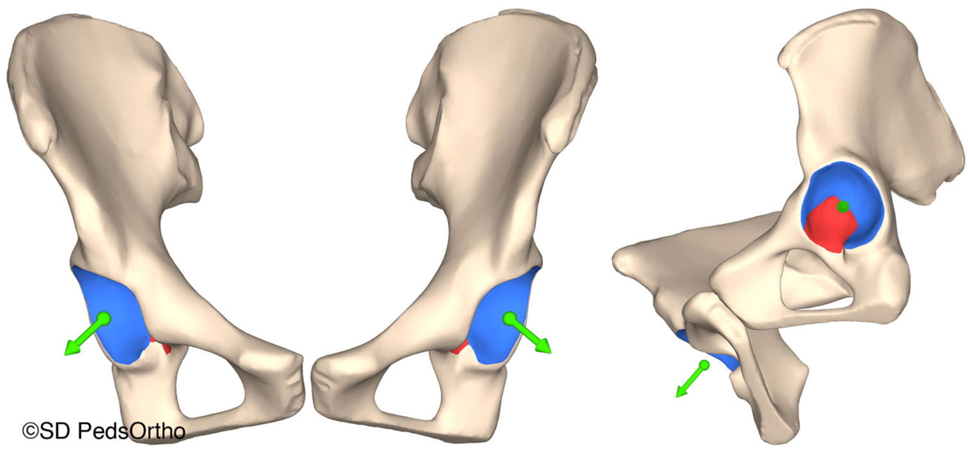

Fig. 2 Three-dimensional vectors were created in the direction of the acetabulum using custom MATLAB software. Acetabular anteversion was calculated as the value of the vector in the axial plane, and acetabular tilt was calculated as the value of the vector in the coronal plane.

the coronal plane) and acetabular version (the angle between the acetabular direction vector and the left-right axis when projected into the axial plane; Fig. 2) [10, 18].

We also developed a novel metric, termed coverage angles to help define acetabular surface topography in 3-D. This allowed us to isolate the cartilaginous weightbearing portion of the acetabulum providing femoral head coverage. The total coverage angle of the acetabulum was defined as the angle between the left-right axis and the line connecting the center of the best-fit sphere with the edge of the acetabulum. The acetabular fossa coverage angle was defined as the angle between the left-right axis and the line connecting the center of the best-fit sphere with the edge of the acetabular fossa. The weightbearing coverage angle was defined as the difference between the two angles (Fig. 3). The acetabulum was divided into eight analysis regions (inferior, inferoposterior, posterior, superoposterior, superior, superoanterior, anterior, and inferoanterior; Fig. 4). Mean coverage angles were reported for each region (measurements by JD). This allowed a novel

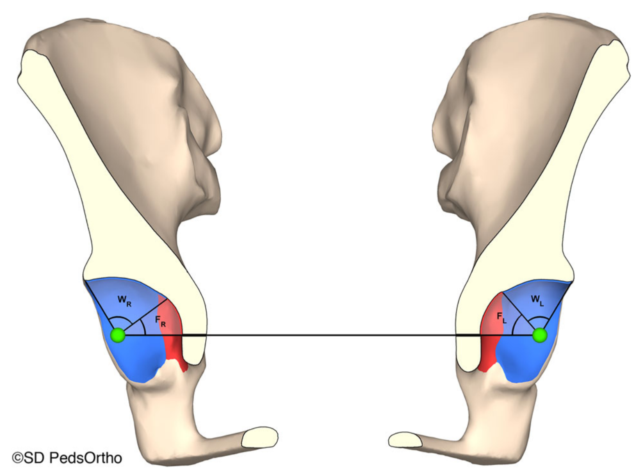

Fig. 3 Novel coverage angles were calculated. The total coverage angle represents the angle between a line connecting center-of-best-fit sphere of both hips and the edge of the acetabulum ($W_{R \text{ or } L} + F_{R \text{ or } L}$). The articular coverage angle ($W_{R \text{ or } L}$) measures the angle of articular cartilage covering the femoral head. A fossa angle ($F_{R \text{ or } L}$) was also calculated. W = weightbearing; F = fossa; R = right; L = left.

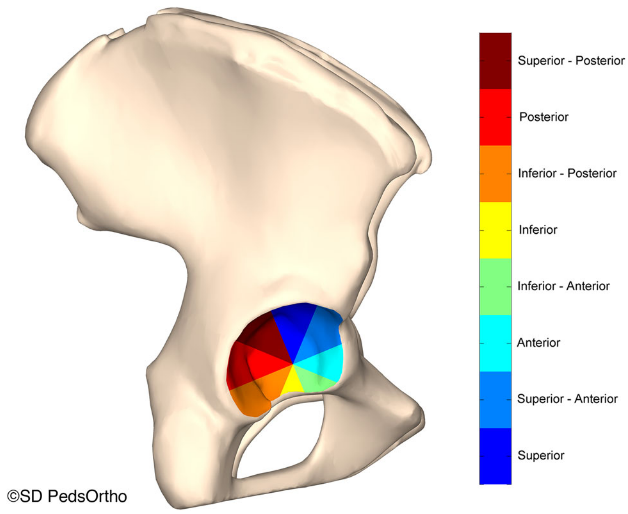

Fig. 4 The acetabulum was divided into eight sections for data analysis.

Table 2. Mean articular surface area (mm^2)

Age group (years)	Gender	Mean	SD	95% CI lower	95% CI upper	p value
8–10	Male	18	2	17	19	0.421
	Female	17	3	17	18	
10–13	Male	22	4	21	23	< 0.001
	Female	20	3	19	20	
13–17	Male	24	3	24	25	< 0.001
	Female	21	3	20	21	

CI = confidence interval.

Table 1. Rate of increase (mm^2/year) in articular surface area of the acetabulum

Age group (years)	Gender	Rate	95% CI lower	95% CI upper	p value
8–10	Male	1.0	0.1	1.8	0.026
	Female	1.0	0.0	1.9	0.042
10–13	Male	1.7	0.9	2.5	< 0.001
	Female	0.9	0.4	1.5	0.002
13–17	Male	0.7	0.1	1.3	0.015
	Female	0.2	−0.3	0.6	0.472

CI = confidence interval.

technique to quantify articular surface area and femoral head coverage specifically by acetabular cartilage.

Pairwise comparisons of continuous variables were evaluated using the t-test. Simple linear regression was used to evaluate the relationship between age and continuous variables. All statistical analysis was conducted using SPSS (Version 12; SPSS, Inc, Chicago, IL, USA). Statistical significance was set at $p < 0.05$ (performed by JDB).

We found 157 patients who met our inclusion criteria. Measurements were obtained on hips of 86 females and 71 males. Data were organized into three age groups: 8 to 10, 10 to 13, and 13 to 17 years.

Results

The rate of increase in articular surface area between males and females was similar in the 8- to 10-year-old patient group (1 mm^2/year versus 1 mm^2/year). Males were increasing in articular surface area at a faster rate than females (2 mm^2/year versus 1 mm^2/year) in children aged 10 to 13 years. In the 13- to 17-year-old patient group, males continued to increase in articular surface area at a rate of 0.7 mm^2/year, whereas female patients were no longer experiencing increases in articular surface area in this age group (Table 1). Mean articular surface area was similar between males and females in the 8- to 10-year-old patient group (18 versus 17 mm^2; $p = 0.421$). Males had greater articular surface area in the 10- to 13-year-old patient group (22 versus 20 mm^2; $p < 0.001$) and the 13- to 17-year-old patient group (25 versus 21 mm^2; $p < 0.001$) (Table 2).

Females had greater mean acetabular version and tilt in all three age groups. Females aged 8 to 10 years had greater acetabular version (7° versus 13°; $p < 0.001$) and greater tilt (32° versus 34°; $p = 0.03$) than males. Females aged 10 to 13 years had greater acetabular version than males (10° versus 17°; $p < 0.001$) and greater tilt than males (34° versus 38°; $p < 0.001$). Females aged 13 to 17 years continued to have greater acetabular version than males (14° versus 20°; $p < 0.001$) and greater tilt (39° versus 41°; $p = 0.023$) (Tables 3, 4).

Increases in tilt correlated with increases in superior coverage angles ($R = 0.797$; $p < 0.001$). Increases in anteversion correlated with increased posterior coverage angles ($R = 0.805$; $p < 0.001$). Posterior and superior coverage increased during the final stages of acetabular development and tended to occur earlier in females than males.

Discussion

The development of the acetabulum is extremely complex and our knowledge is incomplete. Prior studies have described the appearance of secondary ossification centers of the ilium and pubis [19] and have recently characterized the irregular ossification pattern of the posterior wall/ischial secondary ossification center [4]. However, little is known about the development of the articular surface. No studies have quantified how much the acetabular articular surface grows near maturity or how the orientation of the acetabulum changes near maturity.

Our data suggest that the final region of the acetabulum to develop is the posterosuperior region. Not only is total coverage of the femoral head increasing in this region during late childhood and adolescence, but also the surface area of the articular cartilage and associated articular coverage of the femoral head. There is not an increase in the size of the cotyloid fossa, suggesting that not only is the epiphyseal equivalent lateral acetabular hyaline cartilage ossifying, but that there is also appositional articular cartilage and bony growth at the lateral margin of the acetabulum. Traditional radiographic measurements of acetabular retroversion (ie, crossover sign) should be interpreted with caution, especially in early adolescent males. The measurements may be an indication of immaturity rather than true acetabular deformity.

Table 3. Mean acetabular version measured in degrees

Age group (years)	Gender	Mean	SD	95% CI lower	95% CI upper	p value
8–10	Male	7	4	6	8	< 0.001
	Female	13	4	12	14	
10–13	Male	10	4	9	11	< 0.001
	Female	17	6	15	19	
13–17	Male	14	6	13	16	< 0.001
	Female	20	6	19	22	

CI = confidence interval.

Table 4. Mean acetabular tilt measured in degrees

Age group (years)	Gender	Mean	SD	95% CI lower	95% CI upper	p value
8–10	Male	32	3	31	34	0.03
	Female	34	4	33	35	
10–13	Male	34	5	33	35	< 0.001
	Female	38	5	37	40	
13–17	Male	39	5	38	41	0.023
	Female	41	3	40	41	

CI = confidence interval.

There are limitations to our study. It is a retrospective study. A prospective study with repeat CT scans of individual patients would be ideal but not feasible. Images were obtained for nonorthopaedic reasons. Patients were determined to have no hip pain or orthopaedic pathology based on a review of the medical records and assumption that patients with hip pain would have been evaluated at our institution. Thus, the study could possibly include patients with hip pain or dysplasia who were seen at other institutions. A sizable portion of the developing acetabulum is composed of cartilage that is better evaluated with MRI than CT. Thus, we were only able to investigate growth of the bony acetabulum and subchondral articular surface rather than the cartilage itself. A similar technique using MRI with cartilage sequences may provide more information.

There are differences in the pattern of acetabular development between males and females. Females began and completed the final stages of acetabular development slightly earlier than males. This finding is consistent with prior studies [4] and observations regarding earlier closure of the triradiate cartilage in females than males [3]. Furthermore, females had increased acetabular anteversion at maturity compared with males. Results from other work have shown increased acetabular anteversion in adult females compared with adult males [6, 14].

It is unclear why the posterosuperior region of the acetabulum is the last region to develop. It may be related to

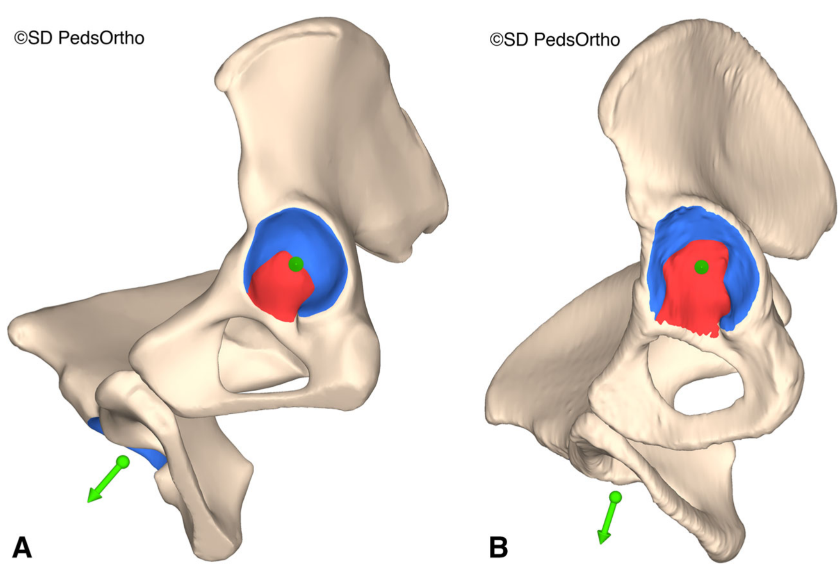

Fig. 5A–B (**A**) This is an oblique view of a normal pelvis looking directly into the acetabulum. The *blue* area is the articular surface and the *red* area is the fossa. (**B**) This is an oblique view of a dysplastic pelvis looking directly into the acetabulum. Notice a larger fossa and diminished articular surface compared with the normal hip.

changes in hip biomechanics because the sagittal alignment of the spine and pelvis change during growth. It has been shown that pelvic incidence increases throughout childhood and adolescence before stabilizing in adulthood [8]. It is plausible that as pelvic incidence increases, stresses from the femoral head are directed toward more posterior regions of the acetabulum, stimulating appositional growth of both bone and cartilage at the periphery of the acetabulum. The increased acetabular anteversion seen in adult females compared with males [6, 14] may correlate with the increased pelvic incidence some studies have shown in adult females [16, 20].

The amount of actual articular cartilage providing coverage of the femoral head is important for long-term prognosis of a hip. A strength of our novel radial sequencing method is that it offers the ability to calculate the amount of articular cartilage, thus providing femoral head coverage in particular regions of the acetabulum (Fig. 5). For example, we have preliminary data in hips with acetabular dysplasia that suggest significantly decreased articular cartilage surface area relative to a normal control. Thus, even after a pelvic-based procedure to improve overall femoral head coverage and stability, decreased articular cartilage surface area and increased contact stresses of the joint surface may lead to premature degeneration in hips despite adequate coverage and stability. This has been suggested in long-term followup studies in the literature for infant hip dysplasia [15] and may hold true for periacetabular osteotomies in more mature patients.

In summary, our study describes a new technique and provides normative data for children and adolescents for the analysis of acetabular development with a focus on development of the articular surface. The technique will also allow more effective analysis of acetabular deformity in a variety of pediatric hip conditions and provide data that will allow both better surgical procedures to correct hip deformity and a better understanding of how shape asymmetry can affect long-term hip function.

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