Age- and Sex-Specific Morphologic Variations of Capital Femoral Epiphysis Growth in Children and Adolescents Without Hip Disorders

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Background: Understanding the development of the capital femoral epiphysis is essential to identify pathologic variations that may lead to cam morphology.

Purpose/Hypothesis: The purpose of this study was to investigate the development of the capital femoral epiphysis during childhood and adolescence, with specific morphologic analysis of the peripheral growth and the metaphyseal surface of the growth plate. We hypothesized that age- and sex-dependent morphologic variations of the peripheral growth (cupping) and surface anatomy (epiphyseal tubercle) of the epiphysis would be evident with increasing age.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: Pelvic computed tomography scans of 80 children and adolescents (range, 8-15 years; n = 10 per age group; 50% male), imaged because of suspected appendicitis, were used to reformat the proximal femur. All patients had asymptomatic hips with no signs or history of hip disorder. We measured the peripheral cupping of the epiphysis and the epiphyseal tubercle dimensions from 3-dimensional models. All measurements were normalized to the epiphyseal diameter. The effect of age on these parameters was evaluated by use of linear regression analysis. A 2-way analysis of variance (ANOVA) was used to compare these parameters between males and females.

Results: The mean epiphyseal cupping increased with increasing age ($R^2 = 0.54$; $P < .001$). The mean normalized epiphyseal cupping was consistently higher in the anterior and posterior directions compared with the inferior and superior locations. Male patients aged 10 and 11 years had lower ($P = .002$) mean epiphyseal cupping compared with female patients of the same age. We observed no difference between male and female participants after 12 years of age ($P > .3$). The normalized epiphyseal tubercle height ($R^2 = 0.08$; $P = .009$), width ($R^2 = 0.13$; $P = .001$), and length ($R^2 = 0.45$; $P < .001$) decreased with increasing age, with no differences between male and female patients. On average, a 2.6-fold increase was found in epiphyseal cupping from 8 to 15 years of age, whereas normalized tubercle height decreased by 0.4-fold.

Conclusion: Peripheral cupping of the epiphysis over the metaphysis increases with age, while the relative epiphyseal tubercle dimensions decrease. Females have an earlier onset of rapid increase in the peripheral cupping compared with males; however, no differences in epiphyseal tubercle dimensions were found between male and female patients. These findings may guide future studies investigating the development of cam morphology, which should consider the surface morphologic characteristics of the capital femoral epiphysis, the growth plate, and the differences in morphologic characteristics according to age and sex.

Keywords: epiphyseal extension; epiphyseal tubercle; cupping; cam FAI; slipped capital femoral epiphysis

Cam morphology is an aspherical contour of the femoral head-neck junction that may lead to abnormal contact against the acetabular rim and symptomatic femoroacetabular impingement.[3] The cause of cam morphology has not been completely elucidated. Supraphysiologic epiphyseal extension on the femoral neck associated with vigorous sports participation around the time of growth plate closure[1,27-29] and subclinical slipped capital femoral epiphysis (SCFE)[2,7] have been described as potential causes. It is possible that during a period of normal growth of the epiphysis, a relative microinstability may predispose to abnormal epiphyseal extension growth in adolescents involved with sports activities[1,24,25] or an epiphyseal slip in obese adolescents.[2,7] Understanding normal development may

The Orthopaedic Journal of Sports Medicine, 6(6), 2325967118781579
DOI: 10.1177/2325967118781579

help elucidate the pathologic variations in the capital femoral epiphysis that lead to the formation of cam morphology during adolescence.

The epiphyseal tubercle is a beaklike projection at the superior and posterior aspect of the metaphyseal surface of the epiphysis, and it has been described as a key stabilizer of the epiphysis.[11,15,25,31,32] One recent study described the anatomic features of the epiphyseal tubercle and showed that its height and surface area relatively decrease with increasing age.[15] This study also subjectively noted a concomitant peripheral growth of the epiphysis around the metaphysis, termed *epiphyseal cupping*.[15] However, those previous studies were limited to analyses of a few cadaveric specimens from osteological collections.[15,31,32] To the best of our knowledge, limited quantitative information is available regarding the peripheral growth of the epiphysis (cupping) and the epiphyseal tubercle within a cohort of healthy, developing adolescents across the appropriate age range. Moreover, prior studies have not investigated potential sex-specific differences in the anatomic features and development of the epiphyseal cupping and epiphyseal tubercle that may have relevant implications given the higher prevalence of cam morphology in male patients.[5,14,17]

The goal of this study was to determine the morphologic characteristics of the capital femoral epiphysis by measuring the epiphyseal diameter, the peripheral cupping of the epiphysis, and the epiphyseal tubercle across different age groups in children and adolescents with asymptomatic hips by using 3-dimensional (3D) image analysis. We hypothesized that there are age- and sex-dependent morphologic variations of the peripheral growth (cupping) and surface anatomy (epiphyseal tubercle) of the epiphysis with increasing age.

METHODS

Study Design and Imaging

Our institutional review board approved this retrospective study. We searched our institutional database for patients undergoing pelvic computed tomography (CT) for evaluation of possible appendicitis from 2008 through 2010. According to our institution protocol, CT scan was the imaging method of choice for evaluation of acute appendicitis during the study period. Patients were positioned supine with the hips extended and the pelvis in a neutral position for CT acquisition. Patients were scanned from the third lumbar vertebra down the level of the proximal femur at 120 kilovolts (peak) [kVp] and 50 to 180 mA depending on patient weight and girth, with a standard gantry rotation of 0.6 seconds and a pitch of 1.375. The CT was acquired helically at 0.625-mm collimation or 1.25-mm collimation. Exclusion criteria were a history of hip injury, disease, or symptoms; the presence of a genetic, neuromuscular, or developmental condition; and low-quality CT images precluding 3D reformatting. Some patients included in this study were participants of a previous study evaluating the alpha angle and femoral head-neck offset in adolescents.[4]

Study Population

We divided patients into age groups from 8 to 15 years (8 groups) and selected 5 males and 5 females per age group. The criteria for patient selection were based on the date of CT acquisition, starting with the oldest date of CT acquisition, until all age and sex categories were complete. We randomly selected the right or the left hip of each patient using a random number generator. A total of 94 patients aged 8 to 15 years who underwent a pelvic CT for evaluation of abdominal pain in the setting of appendicitis during the study period were reviewed. Eight patients were excluded because of associated comorbidities (6 with genetic or neurologic diseases, 1 with craniosynostosis, and 1 with osteochondromatosis). One patient was excluded because of a history of hip pain, and 5 were excluded because of unsuitable CT images (2 with irregular slice thickness and 3 in whom the proximal femur was not completely included in the CT). The study population was composed of 80 patients to allow for assessment of 5 males and 5 females for each age category from 8 to 15 years.

To verify the radiographic normality of each included hip, we measured the alpha angle[22] and epiphyseal tilt angle[2] from the oblique axial plane and the acetabular index angle[33] in the coronal plane and compared these with normal reference values. The maturity status of the proximal femur growth plate was classified as wide-open, open (just a line of cartilage seen between the epiphysis and metaphysis), closing (partial ossification of the growth plate), and closed (complete ossification). This classification was based on the femoral head component of the modified Oxford score of skeletal maturity, and an additional grade was used for the complete ossified growth plate.[1,23,30] The assessments were done in Osirix Viewer (v 8.5, Pixmeo SARL). Details of these assessments are shown in Appendix Figure A1. These assessments were performed by an orthopaedic surgeon (D.A.M.) using the Osirix Viewer.

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One or more of the authors has declared the following potential conflict of interest or source of funding: This study was supported by a grant from the National Institutes of Health (grant R01 AR065462 to A.K.). E.N.N. has received educational support from Arthrex. D.A.M. has received a grant for postdoctoral fellowship from the Sao Paulo Research Foundation (FAPESP grant No. 2016/04376-3).

Ethical approval for this study was obtained by the institutional ethical committee at Boston Children's Hospital.

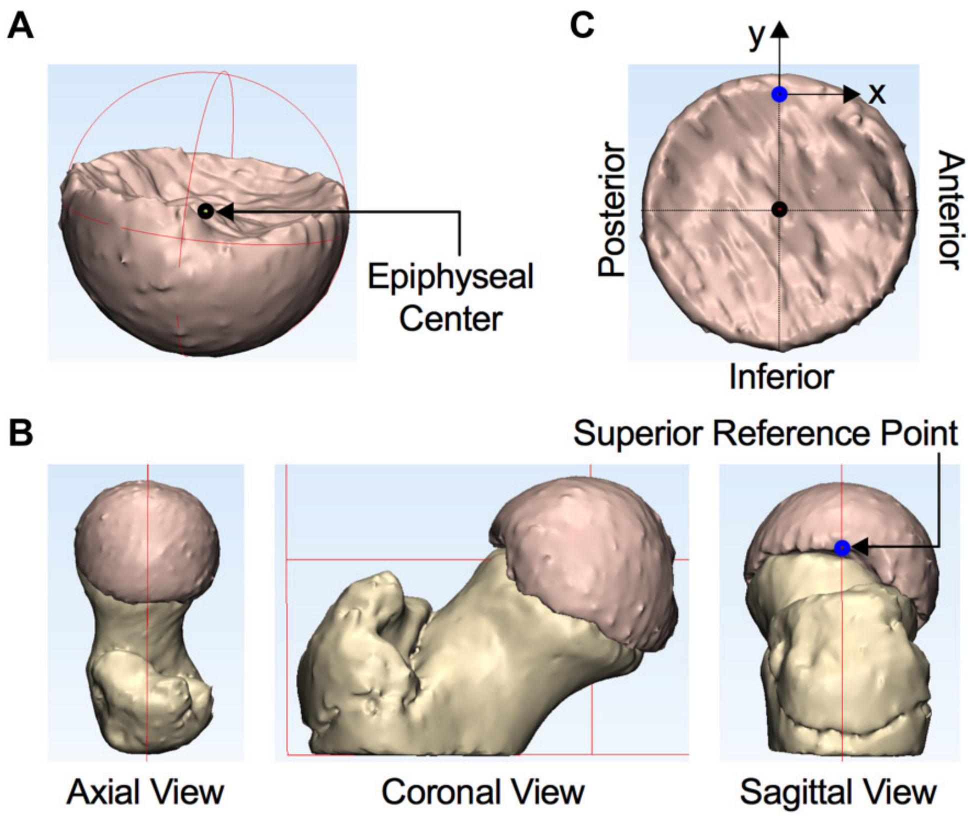

Figure 1. Alignment of the epiphysis in 3D view. (A) Establishing the epiphyseal center using the best-fit sphere. (B) Establishing the superior reference point of the epiphysis as the intersection of the red plane and the most superior point on the epiphysis. (C) Defining the local coordinate system for the epiphysis at the superior reference point (blue dot).

3D Morphologic Analysis of the Capital Femoral Epiphysis Surface

An orthopaedic surgeon (D.A.M.) segmented the thin axial CT slices using image processing software (Mimics v 17.0; Materialise). The epiphysis and the remaining portion of the proximal femur were segmented as 2 independent bodies. For patients with closed growth plate, the sclerotic line of the physeal scar was included in the segmented epiphysis. Segmented masks were then used to reconstruct 3D geometries for each body (Appendix Figure A2). Next, the reconstructed 3D geometries were transferred to 3-matics software (v 9.0; Materialise) without age or sex information so the measurements could be conducted blindly.

An experienced investigator (A.K.) who was blinded to participants' sex and age during the image analysis performed all the measurements. The center and diameter of the epiphysis were determined by use of a best-fit sphere to match the curvature of the epiphyseal surface. The epiphyseal diameter was defined as the diameter of the best-fit sphere. The intersection between the epiphysis and the plane parallel to the longitudinal axis of the femoral neck passing through the greater trochanter was defined as the superior aspect of the epiphysis. This point was then used as the origin to establish a local coordinate system to conduct the epiphyseal measurements (Figure 1).

The true coronal and sagittal cross-sectional views through the center of the epiphysis were used to measure the peripheral cupping of the epiphysis in the anterior, posterior, superior, and inferior locations. The epiphyseal cupping was defined as the distance between the highest peripheral point of the epiphysis and the plane of the epiphyseal center (Figure 2). The average epiphyseal cupping was calculated as the mean of the peripheral cupping measured across the 4 anatomic locations.

The location of the epiphyseal tubercle peak was calculated by selecting the highest point on the tubercle and then measuring its coordinates in relation to the plane through the center of the epiphysis. The true coronal and sagittal cross-sectional views through the tubercle peak were used to measure the tubercle dimensions. Tubercle height was defined as the distance between the tubercle peak and the plane of the epiphyseal center (Figure 2).

Previous studies described the tubercle height as the distance from the tip of the peak to the local nadir of the epiphyseal surface.[15,31] However, we found an inconsistency with establishing the nadir of the epiphyseal surface in the coronal and sagittal cross-sectional views. This was mainly due to substantial irregularities on the epiphyseal surface (Figure 2), which make it extremely challenging to establish a reference to consistently calculate the tubercle height across different patients with different anatomic profiles.

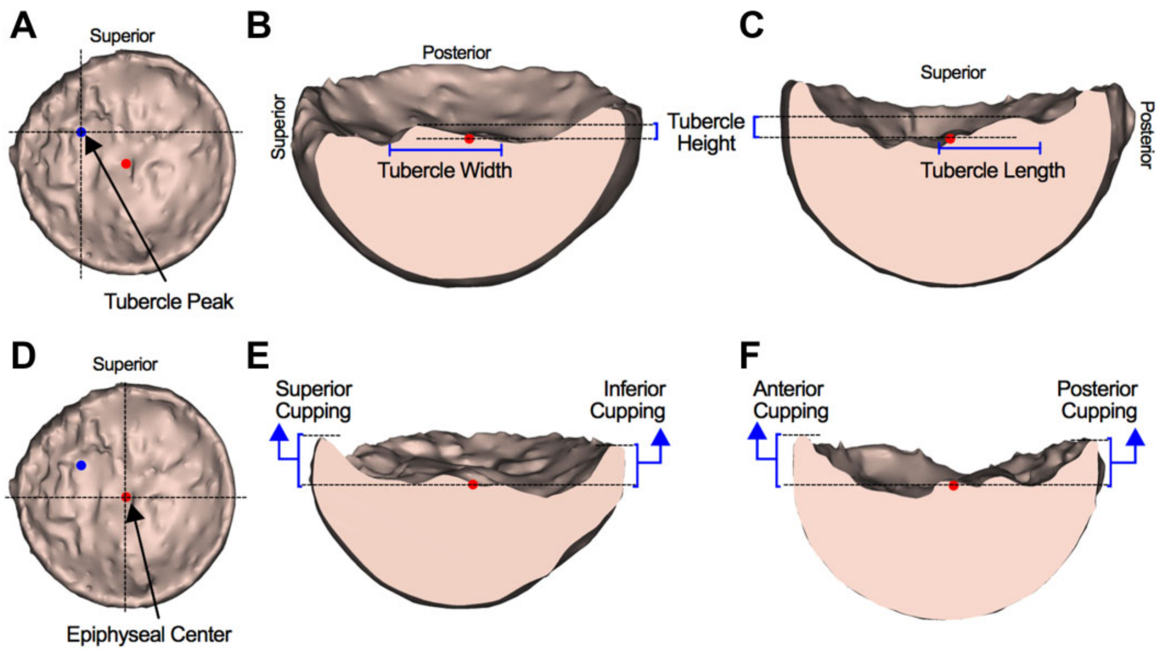

Figure 2. Multiplanar measurements of (A-C) the epiphyseal tubercle size and (D-F) epiphyseal cupping. Panels A and D demonstrate the location of the cross-sectional planes used to quantify tubercle and cupping dimensions.

This assessment is even more complex considering the substantial age-related changes in the morphologic features of the epiphyseal surface. Therefore, tubercle height was measured in both coronal and sagittal views as the distance from the peak to the plane through the center of the epiphysis, and the average values were used for the analysis.

Statistical Analysis

The epiphyseal cupping and the tubercle measurements were normalized to the epiphyseal diameter to account for potential effects of intrapatient variability in size. The effects of age on quantified anatomic outcomes, both absolute and normalized values, were assessed by use of linear regression analysis. All variables, including age, were defined as continuous variables in the model. To further assess the sex differences in quantified anatomic outcomes, the measurements were grouped into 8 subgroups (4 age groups: 8-9, 10-11, 12-13, and 14-15 years for each sex). A 2-way analysis of variance (ANOVA) was used to compare the quantified anatomic feature in each age group between male and female participants (4 pairwise comparisons). The *P* values were then adjusted by use of a Holm-Sidak post hoc correction to account for potential increases in type 1 error due to multiple comparisons. Analyses were done in Prism (v 7.0; GraphPad Software Inc).

To assess the reliability of the anatomic measurements, the same examiner (A.K.) performed the measurements on a subset of 20 hips randomly selected by a random number generator. Variance estimates (ie, between patients and within examiner) were then used to compute the intraclass correlation coefficients (ICCs) for intraobserver reliability (SPSS; IBM Corp). Reliability analyses indicated that most measures of capital femoral epiphysis geometry had good reproducibility, with intraobserver ICCs ranging from 0.74 to 0.98.

RESULTS

All patients had normal hip morphologic features, with alpha, epiphyseal tilt, and acetabular index angles within the normal range. The proximal femoral growth plate was closed in 8 of 10 patients at age 15 years (Table 1).

Epiphyseal Diameter

The epiphyseal diameter increased by age ($R^2 = 0.72$, $P < .001$). Increases in epiphyseal diameter averaged 1.7 mm per year from 8 to 15 years of age. Both male and female participants had similar increases in epiphyseal diameter from 8 to 12 years of age ($P > .3$). However, almost no changes occurred in epiphyseal diameter in female patients from 12 to 15 years of age, whereas male patients showed a continuous increase in epiphyseal diameter, leading to a significantly larger epiphyseal diameter in males compared with females aged 14 and 15 years ($P = .017$).

Peripheral Growth (Cupping) of the Epiphysis

The absolute mean peripheral cupping of the epiphysis increased by age ($R^2 = 0.63$, $P < .001$). Similarly, the mean epiphyseal cupping increased by age ($R^2 = 0.54$,

TABLE 1
Baseline Assessments of Hip Morphologic Features and Skeletal Maturity Status

	Angles, mean ± SD, deg			Proximal Femur Growth Plate Status, No. per Group			
Age, y	Alpha	Epiphyseal Tilt	Acetabular Index	Wide Open	Open	Closing	Closed
8	43 ± 5	8 ± 4	6 ± 5	10	0	0	0
9	40 ± 2	10 ± 4	6 ± 2	10	0	0	0
10	41 ± 4	9 ± 5	7 ± 2	7	3	0	0
11	42 ± 3	6 ± 4	5 ± 4	3	5	2	0
12	42 ± 4	7 ± 6	4 ± 2	1	5	4	0
13	41 ± 5	6 ± 3	4 ± 2	0	4	3	3
14	39 ± 5	6 ± 3	4 ± 1	0	2	5	3
15	38 ± 4	7 ± 3	5 ± 2	0	1	1	8

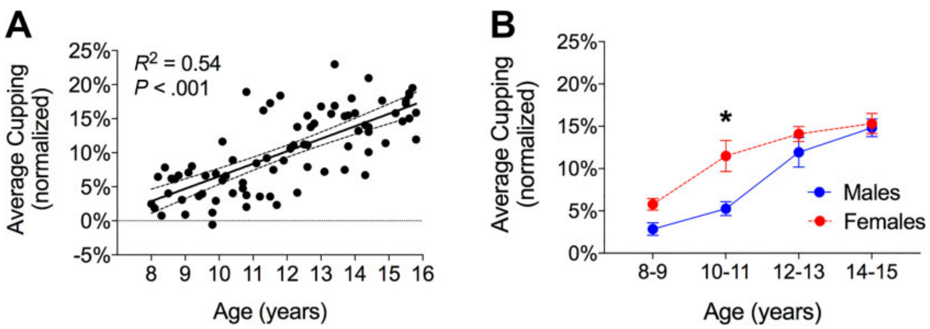

Figure 3. (A) Age-related changes in average epiphyseal cupping. Dashed lines indicate the 95% CI for the regression analysis (N = 80). (B) Comparisons of average epiphyseal cupping between male and female patients. Each data point is the average of all the males or females within corresponding age group (n = 10 per group). Error bars are standard error of the mean (*P = .002). All the measurements are normalized to the epiphyseal diameter and are reported in percentages.

P < .001). The mean normalized epiphyseal cupping increased at all 4 anatomic locations (R^2 > 0.40 and P < .001 for each location analyzed individually). However, the mean epiphyseal cupping was consistently higher in the anterior and posterior directions compared with inferior and superior locations (Appendix Tables A1 and A2). A 1.8% increase was found in the normalized mean epiphyseal cupping per year for 8 to 15 years of age.

A difference in peripheral epiphyseal cupping was found between male and female subjects. Males had slower epiphyseal cupping growth from 8 to 11 years compared with females, which resulted in lower normalized average epiphyseal cupping at ages 10 and 11 (P = .002). However, males showed a faster epiphyseal cupping growth between 12 and 15 years, leading to a similar normalized average epiphyseal cupping between male and female participants after 12 years of age (P > .3) (Figure 3).

Epiphyseal Tubercle

The epiphyseal tubercle peak was eccentrically located in the posterosuperior quadrant of the epiphyseal surface in all patients. No differences in tubercle peak location were found between male and female patients (P > .5) (Figure 4). No variations were noted in the location of the epiphyseal tubercle peak in anteroposterior direction by age (R^2 = 0.03, P = .147). However, the location of the epiphyseal tubercle peak changed with age from superior to inferior (R^2 = 0.11, P = .003).

The absolute height of the epiphyseal tubercle did not vary by age (R^2 = 0.03; P = .156). However, the normalized tubercle height decreased by age (R^2 = 0.08, P = .009). The average (±SD) absolute tubercle height was 1.7 ± 1.5 mm. The normalized tubercle width (R^2 = 0.13, P = .001) and length (R^2 = 0.45, P < .001) decreased by age (Figure 5). Normalized tubercle height, width, and length decreased by 0.5%, 1.1%, and 2.5% per year, respectively, from 8 to 15 years of age. No differences in normalized tubercle dimensions were found between male and female participants (P > .1).

Epiphyseal Tubercle Versus Epiphyseal Cupping

On average, a 2.6-fold increase was found in normalized epiphyseal cupping from 8 to 15 years of age, whereas normalized tubercle height decreased by 0.4-fold within the same time frame (Figure 6).

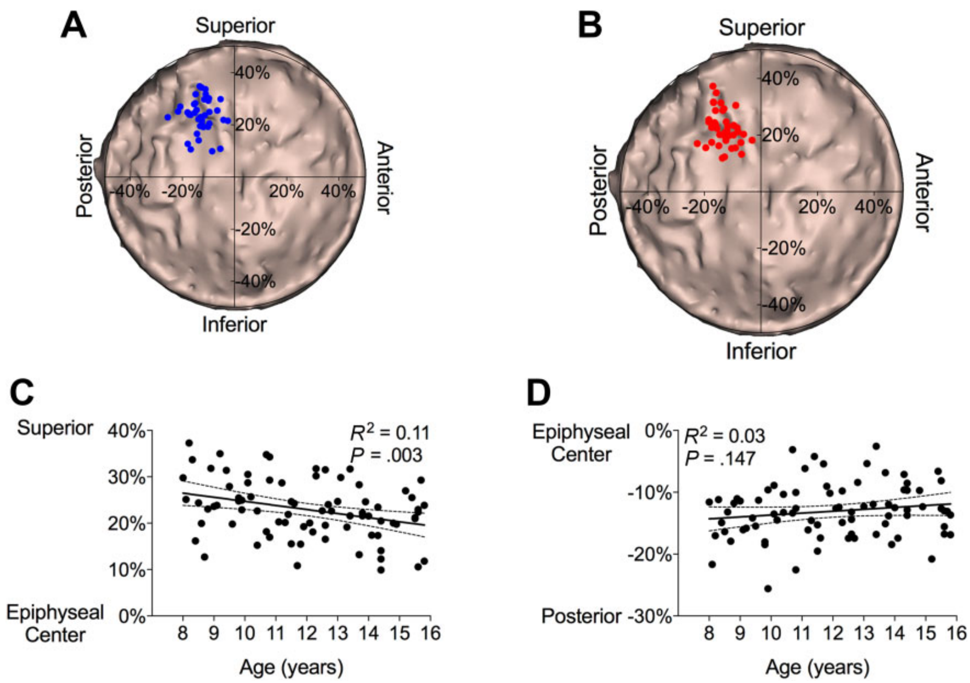

Figure 4. Location of the epiphyseal tubercle peak in (A) males and (B) females (n = 40 per sex group). Changes in the (C) superior-inferior and (D) anterior-posterior location of the epiphyseal tubercle peak by age. Dashed lines indicate the 95% CI for the regression analysis (N = 80). All the measurements are normalized to the epiphyseal diameter and are reported in percentages.

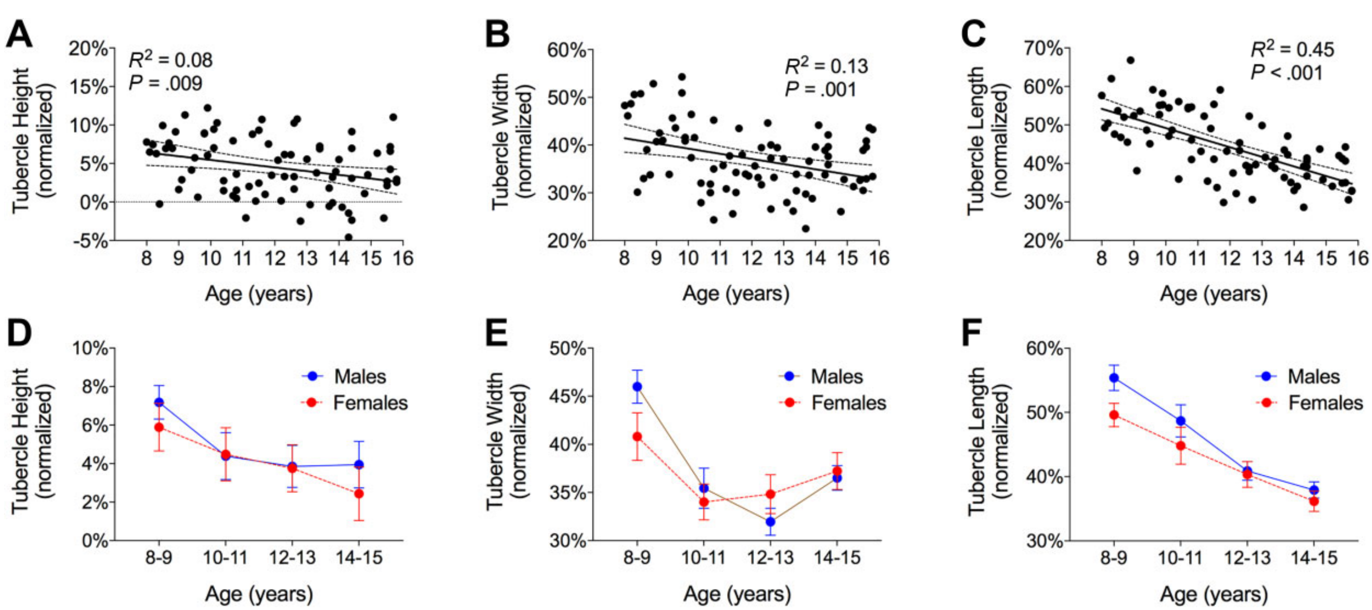

Figure 5. Age-related changes in epiphyseal tubercle (A) height, (B) width, and (C) length. Dashed lines indicate the 95% CI for the regression analysis (N = 80). (D-F) Comparisons of epiphyseal tubercle size between male and female patients. Each data point is the average of all the males or females within corresponding age group (n = 10 per group). Error bars are standard error of the mean. $P > .1$ for all the comparisons. All the measurements are normalized to the epiphyseal diameter and are reported in percentages.

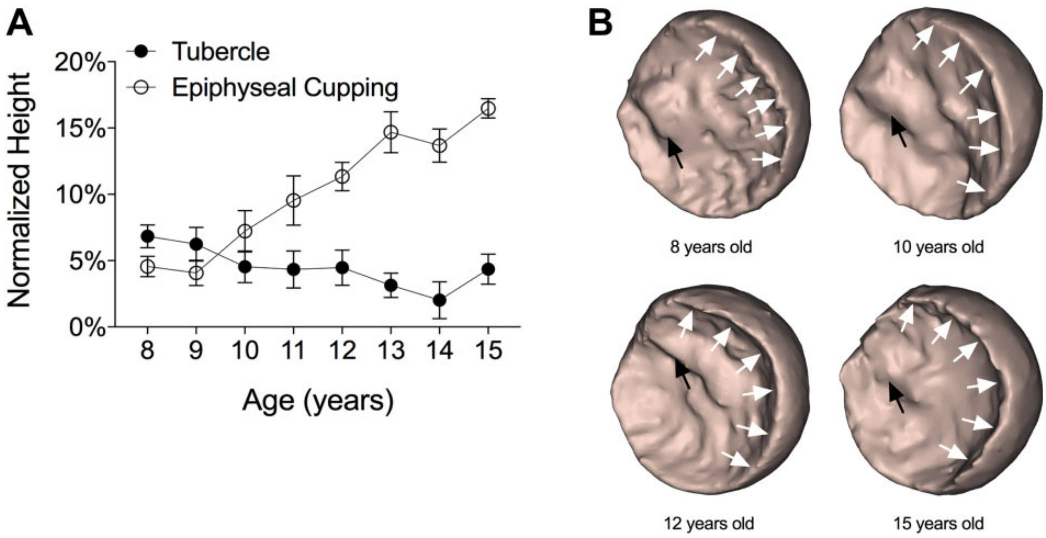

Figure 6. (A) Age-related changes in epiphyseal tubercle height and average epiphyseal cupping. Each point is the average of all the male and female patients within the corresponding age group (n = 10 per group). Error bars are standard error of the mean. All the measurements are normalized to the epiphyseal diameter and are reported in percentages. (B) Representative 3D models of average femoral epiphysis at each age group. The epiphyseal tubercle is indicated with a black arrow, and the anterior aspect of the epiphyseal cupping is indicated with white arrows.

DISCUSSION

This study demonstrated that peripheral cupping of the epiphysis increases while the relative epiphyseal tubercle dimensions decrease with increasing age in children and adolescents. Our findings advance the understanding of capital femoral epiphysis growth by providing quantitative data about the morphologic features of epiphyseal cupping in children and adolescents without hip disease or injury. A relevant finding of this study is that sex influences the peripheral cupping of the capital femoral epiphysis; we did not observe differences in normalized epiphyseal tubercle dimensions during skeletal maturation between male and female participants.

Increased peripheral epiphyseal cupping was a typical growth pattern observed with increasing age in our study. While epiphyseal cupping increased significantly by age, there was a concomitant decrease in normalized epiphyseal tubercle dimensions. This suggests that the increment in the peripheral cupping with increasing age may be a compensatory mechanism for the loss of stability resulting from the decrease in the relative size of the epiphyseal tubercle. Previous studies suggested that this transition in the mechanism that regulates epiphyseal stability may establish a mechanical environment susceptible for the development of SCFE or cam morphology.[15,19-21] Participation in vigorous sports activities may increase shear stress across the growth plate and has been associated with supraphysiologic epiphyseal extension into the anterosuperior metaphysis.[1,26-29] Although some authors have suggested that supraphysiologic epiphyseal extension is a pathologic response to increased recurring mechanical stress at the femoral head-neck junction,[1,24,26,29] others have proposed that excessive extension is an adaptive response to protect the growth plate from increased mechanical stress that could lead to SCFE.[16,19-21] We showed larger peripheral cupping of the epiphysis with increasing age during adolescence, with higher cupping in the anterior and posterior quadrants compared with superior and inferior quadrants. However, further work is necessary to clarify the mechanical factors leading to the supraphysiologic epiphyseal extension in adolescents with cam morphology and whether this is a pathologic or an adaptive response.

We found a significant difference in the peripheral growth of the epiphysis as assessed by epiphyseal cupping between male and female patients. Female patients had a more rapid increase in epiphyseal cupping between the age ranges of 8-9 and 10-11 years, while male patients had their rapid peripheral cupping growth later, between the age ranges of 10-11 and 12-13 years. These differences may be explained by the variations in skeletal growth, which happens chronologically earlier in females than in males.[6,13] Notably, the prevalence of cam morphology is significantly higher in males than in females.[8-10] However, the prevalence of cam morphology is higher in both male[1,24,26,29] and female[12] athletes who engage in vigorous athletic activities early in life. Our findings of rapid peripheral epiphyseal growth at about 8 to 11 years in female participants and 10 to 13 years in male participants are of particular interest because youth athletes who start sports participation before age 12 have been shown to have a higher prevalence of cam morphology compared with athletes who start to play at an older age.[26] Further, cam morphology has been reported to occur as early as 10 years of age.[18] By providing an age range during which morphologic changes take place in the growth plate and the periphery of the epiphysis, our findings may help guide future studies regarding interventions to minimize the prevalence of cam morphology in young athletes.

In this study, we confirmed the location of the epiphyseal tubercle in the posterosuperior quadrant of the epiphysis, as previously reported.[15,31] This location may influence the stability pattern of the epiphysis and may be the fulcrum of a rotational mechanism in SCFE.[15,27] Because the nutrient vessels to the femoral head penetrate the head in the posterosuperior quadrant, it is possible that the epiphyseal tubercle may play a role in preserving those vessels during the development of an acute unstable SCFE, as previously proposed by Liu et al.[15] The absolute epiphyseal tubercle height was on average 1.7 mm, which is lower than the mean value of 4 mm previously reported by Tayton[31]and subsequently by Liu et al.[15] Our mean value was lower because we used the center of the epiphysis instead of the nadir of the epiphyseal surface as the reference for the epiphyseal tubercle height measurement, to improve consistency in this assessment. In line with Liu et al,[15] we found that the normalized epiphyseal tubercle height, length, and width decreased with age. Contrary to the difference observed in the peripheral cupping, we noticed no difference in the epiphyseal tubercle dimensions between male and female patients.

Although it is tempting to assume that these morphologic changes may play a role in cam formation, further studies are necessary to determine how these changes affect stress distribution within the growth plate. Future research should consider the surface anatomic features of the capital femoral epiphysis and growth plate and the differences in morphologic characteristics according to age and sex reported herein. Finally, future studies investigating the impact of early vigorous sports participation and specialization and the development of strategies to minimize the risk of cam formation will benefit from the findings of our study regarding the age of rapid increase in the peripheral epiphyseal cupping and the asynchrony observed in male and female patients.

We acknowledge limitations to our study. First, CT scans are limited to depict the epiphyseal cartilage. Thus, the presented measurements do not take into account potential morphologic variations caused by cartilaginous components of the epiphysis. Despite this limitation, our study provides new data about the development of the capital femoral growth plate with increasing age that will aid in the design of future studies using magnetic resonance technology that can capture cartilaginous changes. Second, chronological age may not correspond to skeletal maturity; however, from a practical point of view, we were more interested in an analysis by chronological age rather than other bone maturity scores, allowing for greater generalizability. Nevertheless, we included information about the status of the femoral growth plate that corresponds to skeletal maturation. Third, despite the large sample size available to assess the effect of age on epiphyseal anatomic features, it is possible that the relatively small subsample size of 5 per age group for each sex may have hindered our ability to detect all the differences between male and female participants. Fourth, measurement errors associated with segmentation and delineation of the epiphysis are possible, and further studies are needed to improve the ability to create 3D reconstruction to include cartilage tissue. The strengths of our study include standardized quality of CT assessment and reformatting for adequate measurement of the variables of interest and the wide range of age groups used to capture morphologic variations during growth.

CONCLUSION

We analyzed the morphologic characteristics of the capital femoral epiphysis and growth plate in a large cohort of children and adolescents aged 8 to 15 years without hip symptoms or hip-related disorders. We showed that while the peripheral cupping of the epiphysis over the metaphysis increased with age, the normalized epiphyseal tubercle height, width, and length decreased. Female patients experienced a rapid increase in peripheral cupping at a younger age compared with male patients, which may be a consequence of earlier skeletal maturation in females. However, no differences were noted for the epiphyseal tubercle measurements between males and females.

REFERENCES

1. Agricola R, Heijboer MP, Ginai AZ, et al. A cam deformity is gradually acquired during skeletal maturation in adolescent and young male soccer players: a prospective study with minimum 2-year follow-up. *Am J Sports Med*. 2014;42(4):798-806.
2. Albers CE, Steppacher SD, Haefeli PC, et al. Twelve percent of hips with a primary cam deformity exhibit a slip-like morphology resembling sequelae of slipped capital femoral epiphysis. *Clin Orthop Relat Res*. 2015;473(4):1212-1223.
3. Beck M, Kalhor M, Leunig M, Ganz R. Hip morphology influences the pattern of damage to the acetabular cartilage: femoroacetabular impingement as a cause of early osteoarthritis of the hip. *J Bone Joint Surg Br*. 2005;87(7):1012-1018.
4. Bixby SD, Kienle KP, Nasreddine A, Zurakowski D, Kim YJ, Yen YM. Reference values for proximal femoral anatomy in adolescents based on sex, physis, and imaging plane. *Am J Sports Med*. 2013;41(9):2074-2082.
5. Clohisy JC, Baca G, Beaule PE, et al. Descriptive epidemiology of femoroacetabular impingement: a North American cohort of patients undergoing surgery. *Am J Sports Med*. 2013;41(6):1348-1356.
6. Dimeglio A. Growth in pediatric orthopaedics. *J Pediatr Orthop*. 2001;21(4):549-555.
7. Goodman DA, Feighan JE, Smith AD, Latimer B, Buly RL, Cooperman DR. Subclinical slipped capital femoral epiphysis: relationship to osteoarthrosis of the hip. *J Bone Joint Surg Am*. 1997;79(10):1489-1497.
8. Gosvig KK, Jacobsen S, Sonne-Holm S, Gebuhr P. The prevalence of cam-type deformity of the hip joint: a survey of 4151 subjects of the Copenhagen Osteoarthritis Study. *Acta Radiol*. 2008;49(4):436-441.
9. Gosvig KK, Jacobsen S, Sonne-Holm S, Palm H, Troelsen A. Prevalence of malformations of the hip joint and their relationship to sex, groin pain, and risk of osteoarthritis: a population-based survey. *J Bone Joint Surg Am*. 2010;92(5):1162-1169.
10. Hack K, Di Primio G, Rakhra K, Beaule PE. Prevalence of cam-type femoroacetabular impingement morphology in asymptomatic volunteers. *J Bone Joint Surg Am*. 2010;92(14):2436-2444.
11. Jonasson PS, Ekstrom L, Sward A, et al. Strength of the porcine proximal femoral epiphyseal plate: the effect of different loading directions and the role of the perichondrial fibrocartilaginous complex and epiphyseal tubercle—an experimental biomechanical study. *J Exp Orthop*. 2014;1(1):4.

12. Kapron AL, Peters CL, Aoki SK, et al. The prevalence of radiographic findings of structural hip deformities in female collegiate athletes. *Am J Sports Med*. 2015;43(6):1324-1330.
13. Kelly PM, Dimeglio A. Lower-limb growth: how predictable are predictions? *J Child Orthop*. 2008;2(6):407-415.
14. Lehmann CL, Arons RR, Loder RT, Vitale MG. The epidemiology of slipped capital femoral epiphysis: an update. *J Pediatr Orthop*. 2006; 26(3):286-290.
15. Liu RW, Armstrong DG, Levine AD, Gilmore A, Thompson GH, Cooperman DR. An anatomic study of the epiphyseal tubercle and its importance in the pathogenesis of slipped capital femoral epiphysis. *J Bone Joint Surg Am*. 2013;95(6):e341-e348.
16. Liu RW, Fraley SM, Morris WZ, Cooperman DR. Validity and clinical consequences of a rotational mechanism for slipped capital femoral epiphysis. *J Pediatr Orthop*. 2016;36(3):239-246.
17. Loder RT, Skopelja EN. The epidemiology and demographics of slipped capital femoral epiphysis. *ISRN Orthop*. 2011;2011:486512.
18. Monazzam S, Bomar JD, Dwek JR, Hosalkar HS, Pennock AT. Development and prevalence of femoroacetabular impingement-associated morphology in a paediatric and adolescent population: a CT study of 225 patients. *Bone Joint J*. 2013;95-B(5):598-604.
19. Morris WZ, Li RT, Liu RW, Salata MJ, Voos JE. Origin of cam morphology in femoroacetabular impingement. *Am J Sports Med*. 2018; 46(2):478-486.
20. Morris WZ, Napora JK, Conry KT, Liu RW. Capital femoral epiphyseal extension may confer physeal stability in slipped capital femoral epiphysis [published online September 22, 2016]. *J Pediatr Orthop*. doi:10.1097/BPO.0000000000000881.
21. Morris WZ, Weinberg DS, Gebhart JJ, Cooperman DR, Liu RW. Capital femoral growth plate extension predicts cam morphology in a longitudinal radiographic study. *J Bone Joint Surg Am*. 2016;98(10): 805-812.
22. Notzli HP, Wyss TF, Stoecklin CH, Schmid MR, Treiber K, Hodler J. The contour of the femoral head-neck junction as a predictor for the risk of anterior impingement. *J Bone Joint Surg Br*. 2002;84(4): 556-560.
23. Popejoy D, Emara K, Birch J. Prediction of contralateral slipped capital femoral epiphysis using the modified Oxford bone age score. *J Pediatr Orthop*. 2012;32(3):290-294.
24. Roels P, Agricola R, Oei EH, Weinans H, Campoli G, Zadpoor AA. Mechanical factors explain development of cam-type deformity. *Osteoarthritis Cartilage*. 2014;22(12):2074-2082.
25. Scheuer L, Black S. The lower limb. In: Scheuer L, Black S, eds. *Developmental Juvenile Osteology*. 1st ed. San Diego, CA: Elsevier Academic Press; 2000:374-467.
26. Siebenrock KA, Behning A, Mamisch TC, Schwab JM. Growth plate alteration precedes cam-type deformity in elite basketball players. *Clin Orthop Relat Res*. 2013;471(4):1084-1091.
27. Siebenrock KA, Ferner F, Noble PC, Santore RF, Werlen S, Mamisch TC. The cam-type deformity of the proximal femur arises in childhood in response to vigorous sporting activity. *Clin Orthop Relat Res*. 2011; 469(11):3229-3240.
28. Siebenrock KA, Schwab JM. The cam-type deformity—what is it: SCFE, osteophyte, or a new disease? *J Pediatr Orthop*. 2013; 33(suppl 1):S121-S125.
29. Siebenrock KA, Wahab KH, Werlen S, Kalhor M, Leunig M, Ganz R. Abnormal extension of the femoral head epiphysis as a cause of cam impingement. *Clin Orthop Relat Res*. 2004;(418):54-60.
30. Stasikelis PJ, Sullivan CM, Phillips WA, Polard JA. Slipped capital femoral epiphysis: prediction of contralateral involvement. *J Bone Joint Surg Am*. 1996;78(8):1149-1155.
31. Tayton K. Does the upper femoral epiphysis slip or rotate? *J Bone Joint Surg Br*. 2007;89(10):1402-1406.
32. Tayton K. The epiphyseal tubercle in adolescent hips. *Acta Orthop*. 2009;80(4):416-419.
33. Tönnis D. General radiograph of the hip joint. In: Tönnis D, ed. *Congenital Dysplasia, Dislocation of the Hip*. New York, NY: Springer; 1987:100-142.

APPENDIX

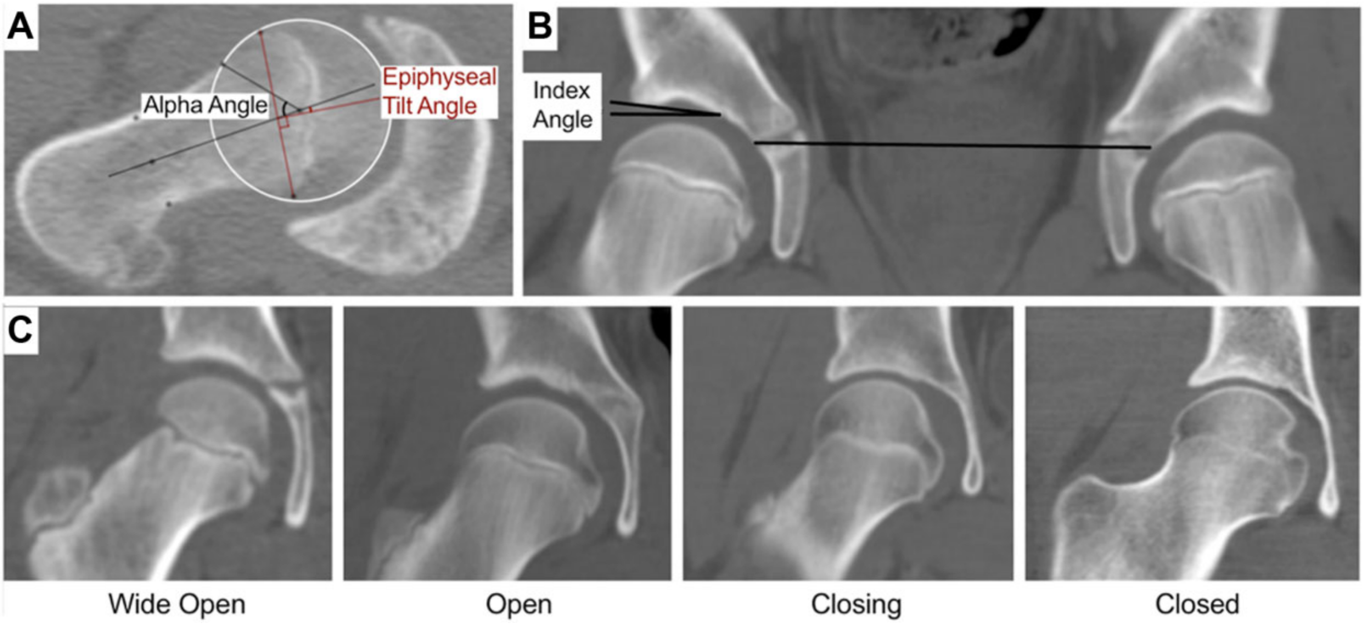

Figure A1. Assessment of (A) alpha angle and epiphyseal tilt angle, (B) acetabular index angle, and (C) proximal femur growth plate status.

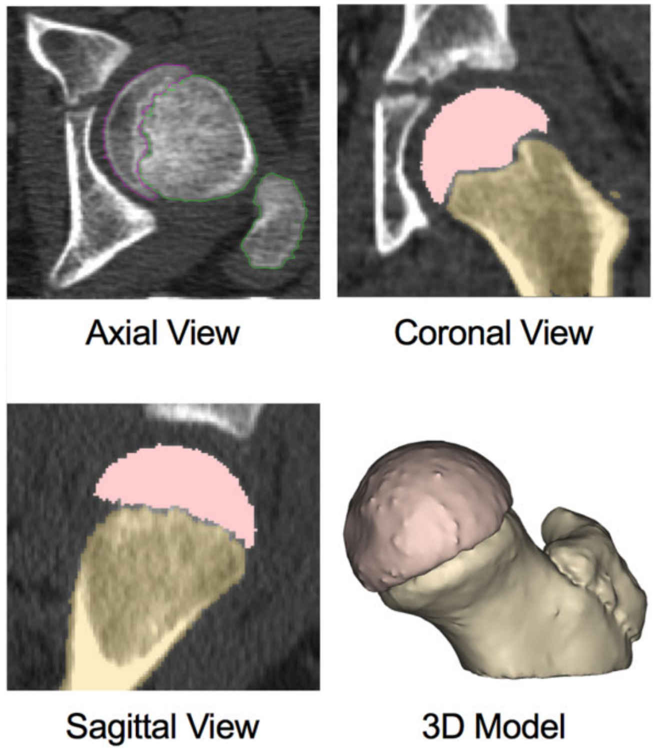

Figure A2. 3D segmentation and reconstruction of the proximal femur in all 3 anatomic planes.

TABLE A1
Mean (SD) of the Absolute Anatomic Measurements for Each Age Group (n = 10 per group)[a]

Anatomic Index	8 y	9 y	10 y	11 y	12 y	13 y	14 y	15 y
Epiphysis								
Diameter	33.7 (2.1)	35.3 (2.8)	36.3 (2)	39.7 (2.4)	41.6 (2.4)	44.4 (2.1)	43.7 (2.6)	45 (3)
Epiphyseal cupping								
Anterior	2.1 (1.2)	2.9 (1.1)	3.5 (2.2)	4.5 (2.6)	5.7 (2.5)	7.5 (2)	6.6 (1.6)	8 (1.7)
Posterior	2.3 (1.1)	1.8 (1.5)	3.9 (1.7)	5.1 (2.3)	6.2 (2)	6.9 (2.1)	7.3 (2.8)	8.1 (1.5)
Superior	0.6 (1.1)	0.1 (1.3)	1 (2.1)	3 (2.9)	4 (1.4)	5.5 (3.1)	5 (2.7)	7 (2.1)
Inferior	1.2 (1.5)	1 (1.8)	2 (1.6)	2.8 (2.7)	3.2 (2)	6 (2.4)	5 (1.6)	6.5 (1.3)
Average	1.5 (0.8)	1.4 (1.1)	2.6 (1.6)	3.8 (2.4)	4.8 (1.6)	6.5 (2)	6 (1.7)	7.4 (0.9)
Epiphyseal tubercle								
Height	2.3 (0.9)	2.2 (1.3)	1.7 (1.3)	1.7 (1.7)	1.9 (1.7)	1.4 (1.3)	0.9 (1.9)	2 (1.6)
Length	17.9 (2.9)	18.2 (1.9)	17.8 (1.9)	17.5 (3.8)	16.5 (2.6)	18.4 (2.4)	16.3 (2.2)	16.6 (2.7)
Width	14.5 (2.9)	15.4 (2.4)	12.8 (2.8)	13.6 (2)	15 (1.9)	13.6 (2)	16.2 (2.2)	16.5 (2.2)

[a]All values are expressed in millimeters.

TABLE A2
Mean (SD) of the Normalized Anatomic Measurements for Each Age Group (n = 10 per group)[a]

Anatomic Index	8 y	9 y	10 y	11 y	12 y	13 y	14 y	15 y
Epiphyseal cupping								
Anterior	6.3 (3.4)	8.2 (3)	9.7 (6.4)	11.2 (6.2)	13.5 (6)	16.9 (4.9)	15.1 (3.8)	17.7 (3.5)
Posterior	6.7 (3.2)	5.2 (4.1)	10.7 (5)	12.7 (5.5)	14.8 (4.4)	15.6 (4.9)	16.8 (6.5)	18.1 (3.3)
Superior	1.7 (3.4)	0.3 (3.7)	3 (6.1)	7.4 (6.9)	9.5 (3.1)	12.5 (7.3)	11.4 (6.1)	15.8 (5)
Inferior	3.5 (4.5)	2.6 (5.1)	5.5 (4.6)	6.9 (6.7)	7.5 (4.5)	13.7 (5.8)	11.4 (3.7)	14.4 (2.8)
Average	4.6 (2.4)	4.1 (3)	7.2 (4.9)	9.5 (5.9)	11.3 (3.4)	14.7 (4.9)	13.7 (4)	16.5 (2.3)
Epiphyseal tubercle								
Height	6.8 (2.7)	6.2 (4)	4.5 (3.8)	4.3 (4.4)	4.5 (4.2)	3.1 (2.9)	2 (4.4)	4.4 (3.6)
Length	53.2 (7)	51.8 (6.4)	49.3 (6.8)	44.2 (9.7)	39.7 (6.2)	41.5 (4.5)	37.2 (4.5)	36.8 (4.7)
Width	43.3 (8.5)	43.5 (5.7)	35.2 (7.4)	34.3 (4.9)	36.1 (5.1)	30.7 (4.7)	37 (5.2)	36.7 (5.1)

[a]All values are expressed as percentages.