The Antiquity of the Cam Deformity

A Comparison of Proximal Femoral Morphology Between Early and Modern Humans

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Background: The precise etiology of cam impingement continues to be incompletely understood. The prevailing hypothesis posits that the deformity arises as a developmental injury prior to skeletal maturation. There is a possible evolutionary role, with an aspherical femoral head affording upright humans better stability. We set out to identify the antiquity of the cam deformity to better understand the comparative roles of modern behavior and evolution in its development.

Methods: We used 249 physical specimens of femora from the Libben osteological collection, a set of bones from an ancient population who lived between the eighth and the eleventh century. These femora were photographed in four different orientations, and six specific proximal femoral angles were measured. The values were also compared with those from modern human femora using the Student t test, with a two-tailed p value of 0.05 denoting significance.

Results: In total, 249 femora from 175 individuals were included in the final analysis. The ages of the individuals ranged between seventeen and fifty-five years. Interobserver and intraobserver correlation was good or excellent for all variables measured. Compared with modern populations, ancient human hips were significantly more anteverted (19.96° versus 12.85°; $p < 0.001$) and varus (true neck-shaft angle, 121.96° versus 129.23°; $p < 0.001$). The alpha angle was significantly lower in ancient humans (35.33° versus 45.61°; $p < 0.001$), and none of the ancient femora met the modern criteria for a cam deformity (an alpha angle of >50°).

Conclusions and Clinical Relevance: It appears that the cam deformity was nonexistent among ancient humans and is perhaps predominantly a product of modern-day stresses. Further clinical investigation into behavioral modifications in adolescence is warranted to potentially prevent the development of deformity and impingement.

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Ganz et al. coined the term *cam* impingement to refer to an "inclusion type" injury, in which an aspherical femoral head-neck junction abuts the anterosuperior aspect of the labrum with hip flexion[1,2]. This chondral impact precipitates pain as well as osteoarthritis in many individuals[3,4]. Our appreciation of the pathoanatomy, symptoms, and treatment of cam impingement is rapidly evolving, but the precise etiology of this condition continues to be incompletely understood.

One hypothesis was that the deformity arises as a developmental abnormality prior to physeal closure, exacerbated by athletic activity in adolescence. Carsen et al. demonstrated that a cam deformity only presented itself after physeal closure, raising suspicion that the deformity arose as a result of developmental changes around the time of physeal closure[5]. Siebenrock et al. measured the location of the physeal plate in elite basketball players and control subjects and found that anterosuperior extension of the physis preceded the development of a cam morphology and was more pronounced in the players than in the controls[6,7]. Additionally, studies have demonstrated that the location of the cam deformity on radial magnetic resonance imaging (MRI) sections corresponds with the location of the physis in skeletally immature individuals[8]. Presumably, repeated running

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and jumping activities in adolescence contribute to either eccentric loading conditions or microtrauma, resulting in an aspherical head.

Evidence has shown that some of the asphericity of the femoral head is attributable to eccentric forces on the femur after the growth plates have closed, resulting in a degenerative cam deformity[8]. The pathophysiology of this postdevelopmental cam deformity has multiple proposed explanations, including decreased hydrostatic pressure at the joint margin and remodeling or shaping of the head over years of motion in the flexion-extension plane[9].

Genetic factors have been known to contribute as well. Pollard et al. examined the prevalence of cam deformities in the siblings of patients with symptomatic femoroacetabular impingement, noting that siblings were 2.8 times more likely than control subjects to exhibit an asymptomatic cam deformity[10]. However, while powerful, that study could not adequately parse out whether the source of the similarities in morphology between siblings was purely genetic or the product of similar activity levels and environmental factors stemming from a shared childhood.

Examination of the evolutionary basis of human osteology offers much insight into the development of the deformity[11,12]. Hogervorst et al. evaluated the morphology of hips and outlined two broad designs that described all mammalian hips—coxa rotunda, in which a spherical femoral head offers increased range of motion at the expense of stability, and coxa recta, in which an aspherical femoral head offers increased stability in runners and jumpers[13]. Although human hips broadly fall into the former category, almost 20% of asymptomatic hips demonstrate morphology closer to coxa recta, or an aspherical femoral head[14].

We examined the antiquity of the cam deformity by analyzing proximal femoral morphology in an early human hunting, farming, and fishing population from the Libben site, a Late Woodland ossuary containing the remains of 1327 individuals[15]. Radiocarbon dating suggests the site, located in Ottawa County, Ohio, was occupied continuously from 1300 to 1000 years before the present and represents about ten generations of a prehistoric population[16]. Analyses of dental wear and tooth eruption, in combination with evaluation of pubic symphyses and auricular surfaces, were used for aging the specimens[16]. The youngest individual was in the first trimester of life, and the oldest was over seventy years of age. Libben represents the largest, most complete, single-occupation cemetery in the Eastern Woodlands and is the most meticulously studied prehistoric ossuary in North America[15,16].

Materials and Methods

Among the 1327 skeletons from the site, 710 were found to be skeletally mature. We excluded any femora that were broken such that the proximal and distal ends of the femur were not in their original orientation. Additionally, we excluded femora that showed signs of bowing, generalized deformity, or damage to proximal femoral landmarks. This finally yielded 175 skeletons with at least one femur in a condition appropriate for this study, or approximately 25% of the total available skeletally mature population. It is quite conceivable that using these 175 individuals to represent an entire population may be flawed. However, we do not believe that our exclusion criteria led to systematic biases in selection, and the final study population had a wide spread of calculated ages (seventeen to fifty-five years) and a good representation of both

TABLE I Demographic Data on the Study Population

Characteristic	Finding *(no. [%])*
Sex	
Male	83 (47.4)
Female	63 (36.0)
Unknown	29 (16.6)
Age*	
17-25 yr	38 (24.1)
26-35 yr	66 (41.8)
36-45 yr	45 (28.5)
46-55 yr	9 (5.7)
Laterality	
Right	45 (25.7)
Left	56 (32.0)
Both	74 (42.3)
Total	175

*Data were not available for seventeen individuals.

TABLE II Intraclass Correlation Coefficients for Each Variable Studied

Variable*	Interobserver Correlation	Intraobserver Correlation
Version	0.97	0.99
Inclination	0.98	0.97
Alpha	0.84	0.85
Beta	0.65	0.71
Apparent NSA	0.84	0.92
True NSA	0.81	0.87

*NSA = neck-shaft angle.

TABLE III Data on the Variables Studied in the 249 Femora

Variable*	Mean *(deg)*	Standard Deviation *(deg)*	Range *(deg)*
Version	19.96	7.73	−5.00 to 48.74
Inclination	18.25	6.90	−6.50 to 36.73
Alpha	35.33	3.87	22.78 to 48.67
Beta	41.46	4.20	28.86 to 54.35
Apparent NSA	129.50	6.58	114.37 to 155.88
True NSA	121.96	5.10	109.19 to 135.78

*NSA = neck-shaft angle.

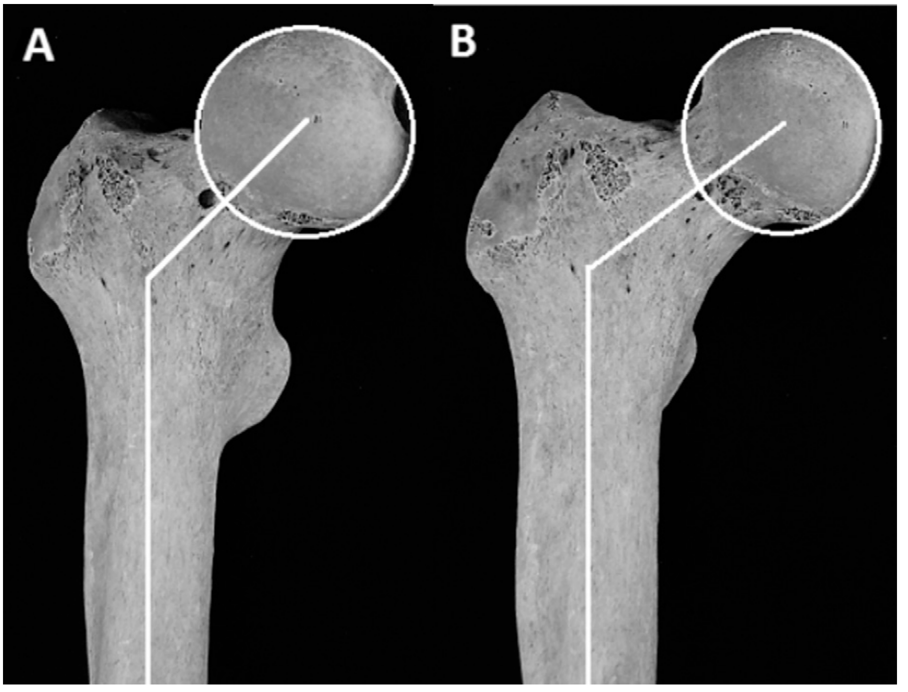

Fig. 1
Radiographic (**Fig. 1-A**) and anatomical (**Fig. 1-B**) anteroposterior views of the femur used to measure the apparent and true NSA, respectively. **Fig. 1-A** The image was obtained with the camera parallel to the table and looking down at the femur, which is resting on the greater trochanter and the femoral condyles. **Fig. 1-B** The image was obtained by rotation of the femur such that the femoral neck was horizontal and in a plane parallel to the table, enabling the measurement of the true NSA. Note that the fovea is not visible, and the lesser trochanter is less visible in Figure 1-B, reflecting the rotation of the femur.

sexes (47.4% male, 36.0% female, and 16.6% unknown). Given the diversity of the final population and our selection criteria, we believe that our results are valid and generalizable across the population.

Each femur was digitally photographed in two positions—anteroposterior and axial—as described by Toogood et al.[17]. A total of four views were generated for each femur. We measured the true and apparent neck-shaft angles (true NSA and apparent NSA), the version angle, the inclination angle, and the alpha and beta angles[17].

Two anteroposterior views were used to measure the apparent NSA and true NSA (Figs. 1-A and 1-B). For determining the apparent NSA (Fig. 1-A), the femur was rested on the medial and lateral condyles distally and the greater trochanter proximally. The camera was placed parallel to the table, looking down at the femur. This represents the typical view seen on a supine anteroposterior radiograph and was used to generate the apparent NSA. For the true NSA (Fig. 1-B), the camera was placed in the same position as for the apparent NSA view. The femur was rotated until the femoral neck was parallel to the table, judged by visual inspection. The lateral femoral condyle was supported in this position with clay prior to photographing. The femoral neck and shaft were in one plane, perpendicular to the view of the camera, creating the true NSA.

The two axial views, termed the *version* and *inclination* views, along with the angles measured, are shown in Figures 2-A and 2-B. The version view (Fig. 2-A) was generated with the camera placed perpendicular to the table, such that the camera pointed down the femoral shaft, i.e., parallel to it, which is consistent with the approach of Kingsley and Olmsted[18]. The femur was rested on its medial and lateral condyles and the greater trochanter. For the inclination view (Fig. 2-B), the camera was in the same position, but with the femur abducted to align

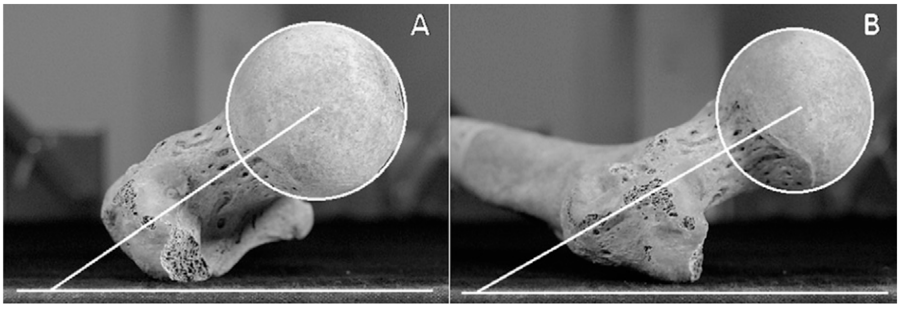

Fig. 2
Axial photographs of the femora used to measure the version (**Fig. 2-A**) and inclination (**Fig. 2-B**) angles. **Fig. 2-A** The image was obtained by placing the camera perpendicular to the table and pointing down the femoral shaft, using the technique described by Kingsley and Olmsted[18]. **Fig. 2-B** The image was obtained with the camera in the same position, but with the femur rotated such that the femoral neck was parallel to the camera. Once again, this placed the femoral neck in a single plane parallel to the camera, and allowed for accurate measurement of the angle made with the table.

TABLE IV Effects of Sex and Age on Variables Studied Using ANCOVA*

	Left		Right	
Dependent Variable or Covariate	Predicted Effect *(deg)*	P Value	Predicted Effect *(deg)*	P Value
Version				
Age	−0.187	0.038	NS	
Sex (female)	NS		NS	
Inclination				
Age	NS		NS	
Sex (female)	NS		2.805	0.042
Alpha				
Age	NS		NS	
Sex (female)	NS		−2.333	0.01
Beta				
Age	NS		NS	
Sex (female)	−2.608	0.002	−2.968	<0.001
Apparent NSA				
Age	NS		−0.179	0.035
Sex (female)	2.976	0.017	NS	
True NSA				
Age	NS		NS	
Sex (female)	2.637	0.009	NS	

*ANCOVA = analysis of covariance, NS = not significant, and NSA = neck-shaft angle.

the femoral neck parallel to the edge of the table. This enabled measurement of the true angle made between the neck and the plane created by the tabletop, generating the inclination angle.

This inclination view was also used to measure the alpha and beta angles (Fig. 3). The alpha angle, first described by Nötzli et al., is a measure of the sphericity of the femoral head[19]. Generally, an alpha angle of >50° is used to define a cam deformity. Since its conception, the alpha angle has been well studied and validated as an accurate measure of the sphericity of the femoral head and a measure of the cam deformity[20,21]. The inclination view mirrors the MRI cut described by Nötzli et al., and the alpha angle was measured as follows. A circle of best fit was drawn encompassing the femoral head, and points were marked where the femur exited this circle anteriorly and posteriorly. A line was drawn from the center of the femoral head down the center of the femoral neck, and the angles between this line and lines from the center of the femoral head to two previously marked points were measured. The anterior angle constituted the alpha angle, while the posterior angle represented the beta angle.

The femora to be photographed were identified by two authors (A.R.M. and L.B.S.) and positioned and photographed by one author (A.R.M.). All authors reviewed every photograph. Measurements of all femora were performed by one author (A.R.M.) on ImageJ software (National Institutes of Health, Bethesda, Maryland). Additionally, a random sample of twenty femora was selected, and measurements were repeated using custom-designed software from MATLAB (The MathWorks, Natick, Massachusetts) by another author (R.B.) to determine interobserver and intraobserver correlation.

All statistical analysis was performed using SPSS software (version 20; IBM, Armonk, New York), with a two-tailed p value of <0.05 denoting significance. Interobserver and intraobserver correlation was measured using the interclass correlation coefficient, with values of >0.65 denoting good correlation and values of >0.75 denoting excellent correlation. Means, standard deviations, and ranges were determined using commonly accepted formulae. Variables were correlated with the age and sex of the population using the analysis of covariance (ANCOVA). Differences between sides in the seventy-four individuals with intact femora bilaterally were assessed using a pairwise Student t test.

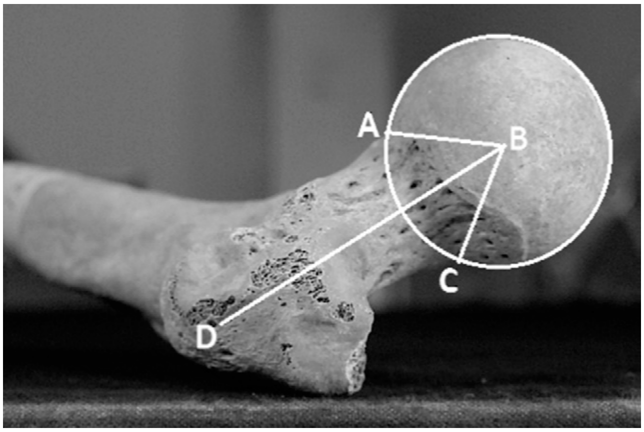

Fig. 3

Inclination view demonstrating the measurement of the alpha and beta angles. A circle was drawn encircling the femoral head, and a line was drawn through the center of the femoral head through the middle of the femoral neck. Points A and C denote the points at which the femoral head “exits” the drawn circle on the anterior and the posterior aspect of the femur. Angle ABD forms the alpha angle, while angle CBD forms the beta angle, which are both a measure of the asphericity of the femoral head.

TABLE V Effects of Laterality on Variables Studied in Seventy-four Individuals with Intact Femora Bilaterally

	Mean Measurements *(deg)*		
Variable*	Left Hip	Right Hip	P Value†
Version	19.67	22.91	0.001
Inclination	18.23	20.49	0.006
Alpha	35.56	34.97	NS
Beta	41.73	41.71	NS
Apparent NSA	131.11	131.15	NS
True NSA	123.32	121.84	0.001

*NSA = neck-shaft angle. †Pairwise Student t test. NS = not significant.

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No funding was received for this study.

Results

A total of 249 femora (130 left and 119 right) from 175 individuals (eighty-three male, sixty-three female, and twenty-nine unknown) were measured (Table I). The femora were obtained from individuals ranging in age from seventeen to fifty-five years.

The interobserver and intraobserver intraclass correlation coefficients showed good or excellent correlation for all variables studied (Table II).

The average alpha angle in this population was 35.33°. The average true NSA was 121.96°, while the average apparent NSA was 129.50°. These hips were quite anteverted, with an average version angle of 19.96° (Table III).

The effect of age and sex on the variables studied was determined using ANCOVA, which allows for regression on one variable while controlling for the effect of the other. In order to ensure independence between groups, this was performed separately on left and right femora. Among the variables tested, the beta angle was the only measurement found to consistently differ by sex in both left and right femora (Table IV). On the basis of pairwise analysis of the measurements of the specimens from the seventy-four individuals with intact femora bilaterally, the only variables found to be significantly different between the left and right femora were version, inclination, and true NSA (Table V).

Discussion

We measured six angles—the angles of version and inclination, the alpha and beta angles, and the true NSA and apparent NSA—using techniques described by Toogood et al.[17], on digital photographs of 249 femora from 175 individuals. We then examined whether these measures varied within the population on the basis of sex, age, and laterality. The effect of age and sex on the morphology of the proximal part of the femur in our population was difficult to interpret. Most of the differences found to be significant were only found unilaterally (Table IV) and were modest in magnitude. Controlling for sex, version in left hips and apparent NSA in right hips were found to have a significant, inverse relationship with increasing age. The beta angle was the only variable found to be different between the sexes in both left and right hips, with males having a slightly higher angle than females, which might point to postdevelopmental changes due to a lifetime of increased loading on the posterior part of the hip.

A comparison of the findings in our study population with those from the Hamann-Todd Osteological Collection, a set of bones from modern humans obtained in the early twentieth century from unclaimed bodies at the Cleveland city morgue, using data from Toogood et al.[17], showed some interesting differences (Table VI). The Libben population hips were much more anteverted than those in the modern humans ($p < 0.001$), probably the result of habitually squatting while at rest. Although the anatomical causation of increased anteversion by squatting is unknown, there is a correlation between the increased femoral version, squatting facets on the distal end of the tibia, platycnemia (a broadening and flattening of the tibia), and the knowledge that ancient populations squatted[22].

The Libben population hips had much lower true NSAs than did the hips in the modern populations ($p < 0.001$). A varus hip can be the result of increased loading prior to skeletal

TABLE VI Comparisons of Measured Angles Between the Libben Collection and the Hamann-Todd Collection

	Libben *(deg)*		Hamann-Todd *(deg)*		
Variable*	Mean	Standard Deviation	Mean	Standard Deviation	P Value†
Version	19.96	7.73	12.85	12.66	<0.001
Inclination	18.25	6.90	9.73	9.28	<0.001
Alpha	35.33	3.87	45.61	10.46	<0.001
Beta	41.46	4.20	41.85	6.92	NS
Apparent NSA	129.50	6.58	130.01	6.45	NS
True NSA	121.96	5.10	129.23	6.34	<0.001

*NSA = neck-shaft angle. †NS = not significant.

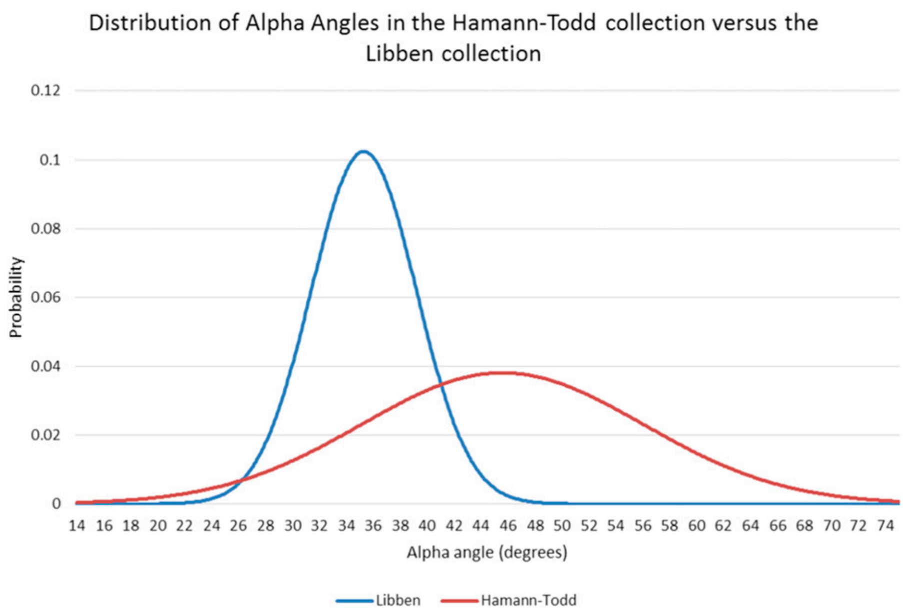

Fig. 4

Normal curves demonstrating the distribution of alpha angles in the Libben collection and the Hamann-Todd collection. Note how the distribution of angles in the Libben collection (early humans) is much narrower and does not include any hips demonstrating a cam deformity, defined as an alpha angle of >50°. The Hamann-Todd collection (modern humans), on the other hand, shows a much wider spread, with almost one-third of the hips demonstrating an alpha angle of >50°.

maturity[23], and it is conceivable that the prolonged walking and heavy lifting prior to adulthood as part of a hunter-farmer lifestyle contributed to this adaptation. What is particularly interesting is that the apparent NSA was similar between the populations. Liu et al. demonstrated that the relationship between true and apparent NSA varies as a function of the cosine of the version angle[24]. The higher the version angle, the higher the apparent NSA for any given true NSA. As a result, despite the low true NSA in the Libben population, the concomitant high version results in an apparent NSA that remains within the range of normal in the modern population. In fact, the apparent NSA and beta angle were the only two variables studied that had similar means, ranges, and standard deviations between the two populations.

As hypothesized, the alpha angle was significantly different between the two populations, with the Hamann-Todd population showing a mean alpha angle 10° higher than that in the Libben population ($p < 0.001$). In fact, none of the 249 hips in the Libben population demonstrated an alpha angle of >50°; it seems that the cam deformity was nonexistent in these early humans. The normal distribution curves for the alpha angles in the two populations illustrated a profound difference (Fig. 4). Given our results, it appears that the cam deformity, defined as an alpha angle of >50°, is a product of modern living.

A comparison of the results in our study with those in investigations of other modern human populations highlighted a similar trend in distribution (Table VII)[6,17,25-30]. Most modern populations studied have an average alpha angle similar to that in the Hamann-Todd sample. The exception is a population of twenty-two young nonathletes, specifically chosen to exclude individuals performing more than two hours of physical exercise a week, reported by Siebenrock et al.[6]. This finding seems to suggest that a potential explanation for the lack of a cam deformity in the Libben population could be a sedentary lifestyle. However, it is unlikely that the Libben population was sedentary. It is more likely that they worked from dawn to dusk just to survive. Heavy lifting and overland hiking to find food, and the toil of early agricultural and fishing methods, were almost certainly a reality for them. It is quite likely that healthy Libben adolescents punished their bones more like an elite athlete than like the present day nonathletes whom Siebenrock et al. used as a control group. The lack of cam deformity in the ancient human population is consequently surprising, given what we know of their arduous lifestyle. It is possible that the differing types of activity between the two populations were the contributing factor. The activity of the basketball players described by Siebenrock et al. was likely short bursts of intense running and jumping[6]. The activity among the ancient humans, on the other hand, would have likely been substantially longer periods of less intensive hiking, walking, and carrying heavy loads. However, this is entirely hypothetical, and further study is necessary to identify the specific biomechanical stresses that predispose individuals to physeal deformity. Additionally, although quite speculative, diet might be an important parameter in shaping the proximal part of the femur of both modern and ancient populations.

Located in what was formerly the Great Black Swamp of northwestern Ohio, the Libben site was an environment that offered a wide variety of edible flora and fauna. As determined through the analysis of storage and garbage pit remains, the population used a wide variety of vegetal and animal foods as

TABLE VII Comparisons of Alpha Angles in the Current Study and Across Modern Populations

Study	Population	Modality*	Age Range *(yr)*	Sample Size	Alpha Angle† *(deg)*
Current study	Cadaveric specimens from 8th-11th c. humans (Ohio, U.S.)	Direct measurement	17-55	175	35.3 (3.9)
Toogood et al.[17] (2009)	Cadaveric specimens of modern humans (Ohio, U.S.)	Direct measurement	18-89	200	45.6 (10.5)
Sutter et al.[25] (2012)	Asymptomatic volunteers (Switzerland)	MRI	20-50	53	49.8 (7.2)
Kang et al.[26] (2010)	Asymptomatic patients (New Zealand)	CT	15-40	50	45.6 (NR)
Pollard et al.[27] (2010)	Asymptomatic individuals (U.K.)	Cross-table lateral radiograph	22-69	83	48.0 (8.0)
Chakraverty et al.[28] (2013)	Asymptomatic young patients (U.K.)	CT	20-40	50	46.0 (NR)
Hack et al.[29] (2010)	Asymptomatic individuals (Canada)	MRI	21.4-50.6	200	40.8 (7.05)
Siebenrock et al.[6] (2011)	Elite basketball players (Germany)	MRI	Physeal closure to 25	16	50.9 (7.3)
Siebenrock et al.[6] (2011)	Nonathletes (Switzerland)	MRI	Physeal closure to 25	22	36.5 (5.5)
Malhotra et al.[30] (2012)	Asymptomatic patients (India)	CT	40-80	85	45.6 (NR)

*CT = computed tomography. †The values are given as the mean, with the standard deviation in parentheses. NR = not reported.

sustenance. Shell remains from nuts such as hickory, seeds from annual plants such as *Chenopodium*, and seeds from berries such as blackberries were found in abundance[31]. The pit remains showed a very heavy reliance on fish from the rich, western basin of Lake Erie. To a much lesser extent, they also ate small game from the surrounding marshes and white-tailed deer[16]. These lines of evidence suggest that the Libben diet was varied, had abundant protein and fiber, and was not high in saturated fats or refined carbohydrates. This is in marked contrast to modern diets in developed countries, where saturated fats and refined carbohydrates are often abundant and dietary fiber is low.

It may be that strenuous physical activity in conjunction with a modern diet, not simply activity alone, is important in the development of this deformity. We speculate that intense activity and a modern diet provoke much cam deformity; average activity and a modern diet (as seen in many contemporary groups), some cam deformity; minimal activity and a modern diet (the controls in the study by Siebenrock et al.), nominal cam deformity; and a punishing lifestyle with an archaic diet (Libben), no cam deformity. Further study into the role of activity and diet modification in adolescence is warranted, and could potentially play a part in the prevention of a cam deformity after skeletal maturity.

The present study has several limitations. First, we looked at only one view in determining the alpha angle, in accordance with the original concept put forward by Nötzli et al.[19]. While this provides a measure of the concavity of the femoral head-neck junction in the anterior position, several studies have suggested that the maximal alpha angle is often at a more anterosuperior position[32,33]. Perhaps a more accurate estimate of the prevalence of the cam deformity could have been obtained by measuring the alpha angle in an oblique plane. However, this would have made it substantially more difficult to standardize femoral positioning and would have increased errors in measurement. Additionally, our method of positioning and photographing femora to measure proximal femoral angles has not been validated with conventional radiographs. Differences between our technique and conventional radiographs could potentially affect the alpha angle, the beta angle, and most substantially, the apparent NSA, depending on the nature of the discrepancy in camera rotation and positioning of the femur. However, while this is an important limitation, our primary goal was to compare the prevalence of the cam deformity between ancient and modern humans to promote an understanding of the antiquity of the deformity. Our photographs were standardized using the methods implemented on the Hamann-Todd collection, allowing us to directly compare our results and generate meaningful conclusions[17].

A more critical limitation is that our knowledge of behaviors in the Libben population is purely hypothetical and based on inferences from dental and osteological specimens, the surrounding area, and knowledge of other, similar populations. Our assumptions about activity and diet may or may not be an accurate recapitulation of life in Libben. However, our goal was to research the antiquity of the cam deformity. It was notably absent in this population. Our comments regarding its development are offered in the spirit of academic speculation, which might lead to testable hypotheses. ■

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