The Shape of the Proximal Femur Influences Acetabular Wear Patterns Over Time

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Abstract

Background Femoroacetabular impingement has been proposed as a cause of early osteoarthritis, but it is not known how this develops over time or whether the shape of the proximal femur influences this risk.

Questions/purposes (1) Which areas of the acetabulum are worn more frequently by individuals with a cam deformity of the proximal femur? (2) Do observed acetabular wear patterns differ based on the etiology of the cam deformity? (3) Do wear patterns of individuals with a cam deformity differ based on an individual's age?

Methods We examined 645 corresponding femora and acetabuli from the Hamann-Todd Osteological Collection and determined the offset and alpha angle using photographs; 370 specimens met inclusion criteria and were examined for signs of wear and the locations of wear were recorded. Specimens were separated into eight subgroups based on age either younger than 40 years or older than 60 years, alpha angle greater or less than 55°, and degree of

anterior head-neck offset. We compared the prevalence of wear between groups in each location.

Results Individuals with abnormal geometry of the proximal femur demonstrated different wear patterns from individuals with normal geometry. There were few differences in wear patterns identified based on the etiology of the femoral deformity. Abnormal femoral geometry was associated with more frequent wear primarily at the anterosuperior acetabulum for individuals younger than 40 years of age and globally for individuals older than 60 years of age.

Conclusion Femoral geometry appears to influence the pattern of acetabular wear occurring over time.

Introduction

Femoroacetabular impingement (FAI), a condition of abnormal contact between the proximal femur and the acetabular rim, has recently gained attention as a cause of early hip pain and may be a precursor to hip osteoarthritis [2, 3]. Cam impingement, a subtype of FAI, results from abnormal contact of the acetabular labrum against either an osseous prominence on the femoral neck or a flattened femoral head-neck junction created by abnormal posterior positioning of the femoral head with respect to the axis of the neck. Although the cam is more accurately conceptualized as a mechanism, such abnormal geometry has been termed a cam deformity of the proximal femur. Studies of asymptomatic volunteers suggest the prevalence of a pathological cam deformity, as defined by the alpha angle, to be 14.0% in men and 5.6% in women [7, 8]. However, the natural history of cam impingement, as it relates to the development of hip osteoarthritis, has not been clearly defined.

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Measurement of proximal femoral geometry such as femoral head-neck offset and the alpha angle can be made from osteological specimens that have been stripped of their surrounding soft tissues, and it is possible to observe signs of abnormal wear in such specimens when these exhibit osteophyte formation, erosions, or exposure of trabecular bone. Although it is impossible to follow these osteological specimens over time, we believe insight into the natural history of a deformity left untreated may be gained by comparing specimens of different ages with subsequent bony changes. This approach has been used to describe the relationship between hip osteoarthritis and geometrical aberrations such as a reduced center-edge angle of Wiberg [16] or a postslip deformity resulting from slipped capital femoral epiphysis (SCFE) [6]. Knowledge of these relationships is important to the practicing orthopaedic surgeon, because the value of new treatments may be better appreciated when the natural history of uncorrected deformities is recognized.

In this study, we used an osteological collection to answer the following questions: (1) Which areas of the acetabulum are worn more frequently by individuals with a cam deformity of the proximal femur? (2) Do observed acetabular wear patterns differ based on whether the cam shape is caused by a bump on the femoral neck or by abnormal posterior positioning of the femoral head with respect to the axis of the neck? (3) With respect to both of these questions, do the wear patterns of individuals with a cam deformity differ based on an individual's age?

Materials and Methods

We selected 645 sets of corresponding femora and acetabuli from the 2972 complete human skeletons in the Hamann-Todd Osteological Collection at the Cleveland Museum of Natural History (Cleveland, OH, USA) based on the following inclusion criteria: evidence of hip osteoarthritis, absence of postmortem damage, and absence of fracture or deformity of the acetabulum including protrusio or coxa profunda. Specimens in this collection had been stripped of all soft tissues by boiling, and the bone had been cleaned with brushes before being degreased with trichloromethane. Photographs were taken of each specimen using standardized views, which consisted of a photograph taken perpendicular to the proximal femur with respect to the long axis of the neck projecting axially down the shaft and of two photographs of the acetabular rim and articular surface to visualize abnormalities. Radiographs were not used for this study, because we set out to observe smaller defects that might be missed radiographically such as pitting and small osteophytes. Femora were measured using MATLAB software (Mathworks, Inc, Natick, MA,

USA) by two graders (AL, SW) concurrently to quantify the degree of posterior offset and the alpha angle [10]. After data had been collected, we selected specimens of age either between 18 and 40 years or older than 60 years at the time of death. Specimens were grouped near the extremes of youth and old age to maximize the chances of finding differences based on age [3].

We were then able to form groups from the data obtained, and these were used to answer the specific questions noted in the Introduction. Based on our inclusion criteria, 645 specimens were included in our study, and 370 were included in the final analysis based on age and inclusion into one of four subgroups defined for each age group; the Bump group ($n = 94$) included specimens with alpha angle greater than 55° [1, 9] and the femoral head not offset more than 0.7 mm behind the axis of the femoral neck; the Offset group ($n = 122$) included specimens with the center of the femoral head positioned more than 1.4 mm behind the neck axis (twice what is considered the threshold of normal); the Cam group ($n = 216$) was a combination of the Bump and Offset groups; the Normal group ($n = 154$) included specimens with alpha angle less than 55° and the center of the femoral head positioned at, or anterior with respect to, the femoral neck axis (Fig. 1). The 275 specimens that were excluded from the analysis did not meet criteria for inclusion in these groups.

The acetabuli were observed for evidence of surface wear, which had caused changes in the underlying bone, being careful to eliminate any specimens with box damage that could confound the results. The curator of the collection was available for consultation when the nature of damage was in question. Osteophytes, erosion, pitting, or exposure of trabecular bone in predetermined anatomic zones were noted and recorded (Fig. 2). Three anatomic areas were defined, these being the rim, the articular surface, and the central rim of the semilunar cartilage. Each anatomic area was then further subdivided into five locations based on position with respect to direction relative to the center of the acetabulum, these being anterior, anterosuperior, superior, posterosuperior, and posterior. This created a total of 15 anatomic zones. The presence of any abnormality within each of these zones was then recorded by a single observer (JJS) who was blinded to the grouping based on proximal femoral geometry, and these observations were tested for interobserver reliability by a second grader (VG) using 60 specimens. A copy of the grading system was available for reference at all times during the data collection period (Fig. 3). The frequency of any wear within each zone was then determined for each subgroup. For clarity, these zones were later superimposed on a clock face, as has become common in describing the acetabulum in reference to FAI [14]. We validated our technique by determining reliability for a subset of 60 specimens

Fig. 1A–C The morphology of the femoral neck was observed using an axially directed photograph perpendicular to the femoral neck. The alpha angle and degree of posterior positioning of the femoral head with respect to the neck axis were measured for each specimen using MATLAB software. Specimens were then divided into groups: the Bump group (**A**) included specimens with alpha angle $> 55^\circ$ and the

head not offset more than 0.7 mm behind the axis of the neck; the Offset group (**B**) included specimens with any alpha angle and the femoral head offset more than 1.4 mm behind the axis of the neck; the Cam group included all specimens in the Bump and Offset groups; the Normal group (**C**) included specimens with alpha angle $< 55^\circ$ and the head not offset by any amount behind the axis of the neck.

(900 wear measurements) by calculating Cohen's kappa, which was 0.502 for interobserver reliability and 0.529 for intraobserver reliability.

After all data had been collected and specimens had been sorted into groups, final demographic information for each group was determined, which consisted of mean age, sex, and race. The mean alpha angle and offset were calculated for each subgroup (Table 1). A Student's t-test was performed to determine differences in these characteristics of the proximal femur. Acetabular wear data were compared between groups for each of the 15 anatomic zones using a parametric test of two proportions (Z-test) to determine whether there were differences between groups in the frequency of wear appearance in each zone. A total of 370 specimens met inclusion criteria for comparison of acetabular wear patterns based on whether or not a cam deformity was present (216 cam, 154 normal). The comparison of acetabular wear patterns between groups based on whether the cam deformity was caused by a bump on the anterolateral femoral neck or by posterior positioning of the femoral head with respect to the neck axis was conducted by comparing the Bump ($n = 94$) and Offset

Fig. 2 Acetabular specimens were observed for evidence of wear, which included osteophytes, erosions, and pitting. These changes could be found in several areas within the same acetabulum. An acetabulum exhibiting a large amount of wear is shown at left with the contralateral acetabulum from the same specimen showing little evidence of wear.

($n = 122$) groups directly. Differences in acetabular wear patterns based on the presence or absence of a cam deformity, with respect to a patient's age, were evaluated by comparing groups based on age either younger than 40 years or older than 60 years at the time of death.

Fig. 3 The grading system we devised for mapping acetabular wear divides the acetabulum into 15 zones. Five zones each comprise the center rim of the semilunar cartilage (C), articular surface (A), and the outer acetabular rim (R), and these correspond to the numbers on a clock face. We examined the anterior (3:00–5:00), anterosuperior (1:00–3:00), superior (11:00–1:00), posterosuperior (9:00–11:00), and posterior (7:00–9:00) areas of the acetabulum. Wear in these areas was noted and recorded to create a map for each specimen.

Results

The proximal femoral geometry of the Cam and Normal groups differed substantially, with the Cam group demonstrating a much larger alpha angle and more posterior positioning of the femoral head with respect to the neck axis. The acetabuli in the Cam group also showed more frequent wear in several areas when compared with the Normal group (Table 1). Specimens demonstrating a cam deformity had a more frequent appearance of acetabular wear centrally from 7:00 to 3:00, on the articular surface from 11:00 to 1:00, and at the rim from 11:00 to 3:00 (Fig. 4).

The Bump and Offset groups demonstrated differences in the alpha angle and the degree of posterior positioning of the femoral head with respect to the neck axis with the latter of these differences being very noticeable. However, direct comparison between the acetabular wear patterns of the Bump and Offset groups demonstrated no differences (Table 2).

Specimens younger than 40 years of age in the Cam group showed more frequent wear than those in the Normal group at the acetabular rim from 11:00 to 3:00. There was also a trend toward more frequent wear ($p < 0.10$) at the

Table 1. The Cam and Normal groups were compared, first based on anatomic characteristics and later based on the corresponding acetabular wear patterns

Group	Cam (n = 216)	Normal (n = 154)	p value
Alpha angle (degrees)	61.9	44.7	< 0.001
Offset	−1.18 mm	0.36 mm	< 0.001

Area	Zone	Number	Frequency	Number	Frequency	p value
Center	3:00–5:00	27	0.12	17	0.11	0.68
	1:00–3:00	69	0.32	33	0.21	0.03
	11:00–1:00	108	0.5	60	0.39	0.04
	9:00–11:00	87	0.4	42	0.27	0.01
	7:00–9:00	25	0.12	2	0.01	< 0.001
Articular	3:00–5:00	12	0.06	10	0.07	0.69
	1:00–3:00	66	0.3	41	0.27	0.43
	11:00–1:00	65	0.3	28	0.18	0.01
	9:00–11:00	21	0.1	9	0.06	0.17
	7:00–9:00	6	0.03	5	0.03	0.83
Rim	3:00–5:00	56	0.26	40	0.26	0.97
	1:00–3:00	159	0.73	97	0.63	0.04
	11:00–1:00	127	0.59	72	0.47	0.03
	9:00–11:00	72	0.33	44	0.29	0.35
	7:00–9:00	65	0.3	40	0.26	0.4

The Cam group demonstrated significantly greater alpha angles and posterior positioning of the femoral head with respect to the femoral neck axis. There were several areas of difference in acetabular wear frequency with the Cam group demonstrating more frequent wear in these areas.

articular surface from 11:00 to 5:00 (Table 3). Specimens older than 60 years of age in the Cam group showed more frequent wear centrally from 7:00 to 3:00, on the articular surface from 9:00 to 1:00, and at the rim from 7:00 to 1:00 (Table 4). The locations of wear differences changed based on whether the specimens were younger than 40 years of age or older than 60 years of age (Fig. 5A). We found no differences between the Bump and Offset groups in specimens younger than 40 years of age, but a trend toward more frequent acetabular rim wear from 9:00 to 11:00 in the Offset group was identified. For specimens older than 60 years of age, more frequent wear was identified in the Offset group centrally from 1:00 to 3:00, and a trend toward more frequent wear was identified on the articular surface from 11:00 to 1:00. A trend toward more frequent wear in the Bump group was identified on the articular surface from 1:00 to 3:00 (Fig. 5B).

Discussion

The prevalence of a cam deformity within the general population is believed to be high despite the fact that hip pain in younger individuals is comparatively rare [8].

Fig. 4 A comparison of wear patterns between specimens of all ages with and without a cam deformity was performed. Specimens demonstrating a cam deformity were found to have more frequent appearance of acetabular wear centrally from 7:00 to 3:00, on the articular surface from 11:00 to 1:00, and at the rim from 11:00 to 3:00.

Although unproven, it is also believed that this deformity usually develops over time and may be a cause of hip osteoarthritis, even in those individuals who do not exhibit pain early in life [2, 5]. The current conceptualization of cam impingement, as presented by Ganz et al. [5], states that as the femoral cam deformity comes into contact with the acetabulum, the labrum is pushed up and the labral-chondral junction is exposed to increased shear stresses. Recent studies have implicated labral damage in the progression to early osteoarthritis, because damage to the labrum alters joint stability, impairs the sealing mechanism of the labrum over the femoral head and neck, and decreases cartilage consolidation [4]. By performing an osteological study of specimens with and without the cam deformity, we have attempted to further substantiate this concept of osteoarthritis progression by answering the following questions: (1) Which areas of the acetabulum are worn more frequently by individuals with a cam deformity of the proximal femur? (2) Do observed acetabular wear patterns differ based on whether the cam shape is caused by a bump on the femoral neck or by abnormal posterior positioning of the femoral head with respect to the axis of the neck? (3) With respect to both of these questions, do the wear patterns of individuals with a cam deformity differ based on an individual's age?

Table 2. The Bump and Offset groups were compared, first based on anatomic characteristics and later based on the corresponding acetabular wear patterns

Group	Bump (n = 94)	Offset (n = 122)	p value
Alpha angle (degrees)	63.5	60.7	0.01
Offset	−0.11 mm	−2.06 mm	< 0.001

Area	Zone	Number	Frequency	Number	Frequency	p value
Center	3:00–5:00	13	0.14	14	0.12	0.61
	1:00–3:00	26	0.28	43	0.35	0.24
	11:00–1:00	49	0.52	59	0.48	0.59
	9:00–11:00	37	0.39	50	0.41	0.81
	7:00–9:00	12	0.13	13	0.11	0.63
Articular	3:00–5:00	7	0.07	5	0.04	0.29
	1:00–3:00	28	0.30	37	0.30	0.94
	11:00–1:00	27	0.29	37	0.30	0.80
	9:00–11:00	7	0.07	14	0.12	0.31
	7:00–9:00	2	0.02	4	0.03	0.60
Rim	3:00–5:00	26	0.28	30	0.25	0.61
	1:00–3:00	69	0.73	88	0.72	0.83
	11:00–1:00	51	0.54	73	0.60	0.42
	9:00–11:00	26	0.28	26	0.21	0.28
	7:00–9:00	31	0.33	31	0.25	0.22

The Bump group demonstrated significantly greater alpha angles, whereas the Offset group demonstrated more posterior positioning of the femoral head with respect to the femoral neck axis. There were no areas of difference in acetabular wear frequency detected between groups.

The conclusions of our study must be viewed in light of several limitations. First, we used a novel grading scheme with limited interobserver agreement: the overall agreement between observers for 900 measurements was greater than 75% (Cohen's kappa = 0.502). We nonetheless believe our attempt at mapping acetabular wear provides important data despite the lack of validation of the scheme and the limited reliability. Second, the use of an osteological collection limits the conclusions that may be drawn from the data. The specimens we studied lacked articular cartilage and labral tissue, and thus wear needed to have been severe enough to cause changes in the underlying bone to be observed. However, all specimens were prepared in the same manner, and we believe wear significant enough to cause osseous changes is likely to be clinically important. It was also not possible to assess whether these individuals had hip pain or whether they became symptomatic early or late in life, and other factors such as activity level could not be assessed. Third, the orientation of the acetabulum, as it relates to pincer-type FAI, was unknown because it was not possible to make these measurements using disarticulated skeletons. However, despite not knowing the orientation of the acetabulum, we believe

Table 3. The Cam and Normal groups for specimens younger than age 40 years at the time of death were compared, first based on anatomic characteristics and later based on the corresponding acetabular wear patterns

Group		Cam (n = 154)		Normal (n = 80)		p value
Alpha angle (degrees)		61.4		45.7		< 0.001
Offset		−1.20 mm		0.30 mm		< 0.001
Area	Zone	Number	Frequency	Number	Frequency	p value
Center	3:00–5:00	11	0.08	3	0.04	0.24
	1:00–3:00	33	0.21	13	0.16	0.36
	11:00–1:00	66	0.43	28	0.35	0.24
	9:00–11:00	45	0.29	18	0.23	0.33
	7:00–9:00	9	0.06	2	0.03	0.32
Articular	3:00–5:00	4	0.03	6	0.08	0.09
	1:00–3:00	40	0.26	12	0.15	0.06
	11:00–1:00	42	0.27	13	0.16	0.06
	9:00–11:00	9	0.06	4	0.05	0.75
	7:00–9:00	2	0.01	1	0.01	0.99
Rim	3:00–5:00	23	0.15	10	0.13	0.68
	1:00–3:00	102	0.66	37	0.46	0.003
	11:00–1:00	77	0.5	26	0.33	0.01
	9:00–11:00	34	0.22	14	0.18	0.47
	7:00–9:00	28	0.18	12	0.15	0.56

The Cam group demonstrated significantly greater alpha angles and posterior positioning of the femoral head with respect to the femoral neck axis. There were several areas of difference in acetabular wear frequency with the Cam group demonstrating more frequent wear in these areas.

our data relating to femoral geometry are of value and are in agreement with previous clinical work [2]. Finally, we did not attempt to quantify the severity of wear at each location. By placing the focus of our investigation instead on the pattern of wear that could be observed, we have provided data that do not attempt to comment on whether a particular deformity caused changes that might have been particularly debilitating in life, but instead simply provide information about the relationship of femoral geometry and the location of acetabular wear.

We observed a difference in the acetabular wear patterns of individual specimens based on whether a cam deformity of the proximal femur was present. The presence of a cam deformity was associated with an increased prevalence of acetabular wear at the anterosuperior rim as well as centrally deep within the acetabulum. This finding is in agreement with earlier work by Goodman et al. [6] published using the same osteological collection in 1997. These authors graded the severity of global hip osteoarthritis and found more severe femoral and acetabular changes occurred in individuals with postslip morphology. We believe our study provides further evidence of a wear

Table 4. The Cam and Normal groups for specimens older than age 60 years at the time of death were compared, first based on anatomic characteristics and later based on the corresponding acetabular wear patterns

Group		Cam (n = 62)		Normal (n = 74)		p value
Alpha angle (degrees)		64.3		43.7		< 0.001
Offset		−1.16 mm		0.43 mm		< 0.001
Area	Zone	Number	Frequency	Number	Frequency	p value
Center	3:00–5:00	16	0.25	14	0.19	0.40
	1:00–3:00	36	0.57	20	0.27	< 0.001
	11:00–1:00	42	0.67	32	0.43	0.006
	9:00–11:00	42	0.67	24	0.32	0.001
	7:00–9:00	16	0.25	0	0.0	0.04
Articular	3:00–5:00	8	0.13	4	0.06	0.16
	1:00–3:00	26	0.41	29	0.39	0.81
	11:00–1:00	23	0.37	15	0.20	0.03
	9:00–11:00	12	0.67	5	0.07	0.03
	7:00–9:00	4	0.06	4	0.05	0.80
Rim	3:00–5:00	33	0.52	30	0.41	0.20
	1:00–3:00	57	0.90	60	0.81	0.14
	11:00–1:00	50	0.79	46	0.62	0.03
	9:00–11:00	38	0.60	30	0.41	0.02
	7:00–9:00	37	0.59	28	0.38	0.01

The Cam group demonstrated significantly greater alpha angles and posterior positioning of the femoral head with respect to the femoral neck axis. There were several areas of difference in acetabular wear frequency with the Cam group demonstrating more frequent wear in these areas. This wear pattern was different from that seen in the younger group of specimens.

pattern in FAI that does not strictly involve the anterosuperior acetabular rim and one that deserves further study.

The osteological specimens we studied demonstrated very few differences in wear patterns based on whether the cam deformity was primarily caused by bone buildup or abnormal positioning of the femoral head posteriorly with respect to the femoral neck axis. The prototypical deformity of the proximal femur characterized by abnormal posterior offset occurs in cases of subclinical SCFE, which is considered to be a static deformity occurring early in life. Although the natural history of the development of an anterolateral bump at the femoral head-neck junction is not known, this region of the proximal femur is believed to be the last part of the neck to ossify [11, 15] and the deformity is considered to be more progressive. Given our findings, it may be the case that any abnormal abutment of the proximal femur against the acetabular rim with hip motion has the potential to cause global damage over time. Whether this abutment is caused by the development of bump morphology on the anterosuperior neck or by posterior slippage of the capital femoral epiphysis may be less important.

Fig. 5A–B A comparison of acetabular wear patterns based on both morphology and age was performed. **(A)** Specimens younger than 40 years of age in the Cam group showed more frequent wear than those in the Normal group at the acetabular rim from 11:00 to 3:00. There was also a trend toward more frequent wear ($p < 0.10$) at the articular surface from 11:00 to 5:00. Specimens older than 60 years of age in the Cam group showed more frequent wear centrally from 7:00 to 3:00, on the articular surface from 9:00 to 1:00, and at the rim from 7:00 to 1:00. **(B)** No large differences between the Bump and Offset groups were found in specimens younger than 40 years of age, but a trend toward more frequent acetabular rim wear from 9:00 to 11:00 in the Offset group was identified. For specimens older than 60 years of age, more frequent wear was identified in the Offset group centrally from 1:00 to 3:00, and a trend toward more frequent wear was identified on the articular surface from 11:00 to 1:00. A trend toward more frequent wear in the Bump group was identified on the articular surface from 1:00 to 3:00.

By addressing age as a factor in the appearance of wear within the acetabulum, we hoped to provide insight into the natural history of cam impingement. Individuals younger than 40 years of age demonstrated differences between the Normal group and the Cam group at the acetabular rim between 11:00 and 3:00 and some increased wear on the articular surface from 11:00 to 5:00. This is consistent with the described injury pattern of FAI. Specimens older than age 60 years at the time of death demonstrated differences between the Cam and Normal groups, which we found both centrally and posteriorly. This may be evidence of global osteoarthritis resulting from loss of the seal of the labrum over the femoral head and possibly of a contrecoup wear

pattern, which has been proposed to occur in pincer-type FAI [12, 13]. Although it deserves further study, calcification of the labrum after repeated damage caused by a cam deformity may have contributed to this posterior shifting of wear patterns over time. Our results are in agreement with those of Beck et al. [2], who performed a similar study in patients with cam-type morphology undergoing surgical dislocation of the hip and noted that the most severe acetabular damage occurred anterosuperiorly but that some of these patients also demonstrated osseous metaplasia or ossification of the posteroinferior labrum. It should be noted that the most commonly observed sites of wear for all groups were at the acetabular rim between 11:00 and 3:00, and in fact this is probably why no differences between the Cam and Normal groups were identified in these locations in older individuals. These appear to be the areas that sustain the greatest attritional damage over time regardless of the shape of the proximal femur.

Overall, our observations suggest differences in acetabular wear patterns are discernible based on whether an individual has a cam deformity of the proximal femur and that these differences change based on age. The etiology of the cam deformity appears to only subtly influence the type of wear experienced by the acetabulum over time, because both an anterosuperior osseous bump on the femoral neck and a postslip deformity are associated with global wear, which is different from that found in osteological specimens without a cam deformity. The increased prevalence of posterior and central acetabular wear in specimens with a cam deformity is an important finding, because it may help to further explain why certain individuals develop global osteoarthritis of the hip. An understanding of the underlying biomechanics of this process may help guide treatment of young patients undergoing hip preservation surgery for FAI.

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