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**Exploring Femoroacetabular Impingement: An Examination of the Evolution of the
Disease and Implications for the Development of Osteoarthritis**

A Thesis Submitted to the
Yale University School of Medicine
in Partial Fulfillment of the Requirements for the
Degree of Doctor of Medicine

by
Raghav Badrinath
Class of 2015

EXPLORING FEMOROACETABULAR IMPINGEMENT AND ITS IMPLICATIONS FOR THE DEVELOPMENT OF OSTEOARTHRITIS. Raghav Badrinath, Daniel R. Cooperman. Section of Pediatric Orthopedics, Department of Orthopedics and Rehabilitation, Yale University, School of Medicine, New Haven, CT

Femoroacetabular impingement (FAI) has been recently elucidated as an explanation for cases of hip osteoarthritis (OA) that were previously categorized as “idiopathic”. We examine three questions related to FAI - the antiquity of the cam deformity, the role of overcoverage in hip osteoarthritis and the mechanism of impingement with acetabular retroversion.

To examine the antiquity of the cam deformity, we performed proximal femoral measurements on 175 femora obtained from 8th-11th century humans living in present-day Ohio. Besides descriptive analysis of central tendencies, we also compare these to measurements on modern femurs.

For the other two questions, we looked at hip radiographs in patients below the age of 35, and compared these to OA-free hips from patients above 65 years of age, to determine the hips that “make it” to 65 without developing OA. We also do this same comparison looking at the difference in the prevalence of retroverted hips between the two populations. Proportions of hips with retroversion signs or desired CE angles were compared using chi-squared tests.

We found that the femurs from the Libben collection were significantly more varus and anteverted than modern femurs. Additionally, the mean alpha angle was 35°, significantly lower than the mean 45° in modern humans. None of the femurs in the Libben collection had a cam deformity. It appears that the cam deformity is a relatively new deformity.

With overcoverage, there were 477 younger patients (mean CE angle 35°) and 446 older patients (mean CE angle 37°). The proportion of overcovered hips (hips with a CE angle > 45°) was not statistically different between the two populations, suggesting that an overcovered hip does not automatically predispose individuals to arthritis.

Finally, we found that the proportion of retroverted hips with a CE angle over 30° were significantly different between the old and young groups. It appears that retroversion does, in fact, lead to accelerated arthritis. However, this seems to require a threshold of coverage to cause impingement.

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Chapter One – Introduction

Osteoarthritis of the Hip – a Historical Perspective

Osteoarthritis refers to the disease process where protective articular cartilage is worn down over time causing increased friction at the bone-bone interface, resulting in significant pain with movement.¹ The knee, hand and hip are the most commonly affected joints. In 2005, nearly 21.4 million Americans were believed to have arthritis or other joint problems.² With a rapidly aging population, and increasing rates of obesity (a risk factor for hip and knee osteoarthritis), this number is expected to nearly double to 41.1 million by 2030.³ On top of an obvious human cost in terms of pain, disability and impairment, studies estimate direct medical costs from osteoarthritis range from \$1,963 to \$2,827 per person per year.⁴ These direct medical costs include medication costs directly related to treatment, including over the counter non-steroidal anti-inflammatories (NSAIDs) often used as first line treatment, injections and opioids, as well as costs related to primary and specialist physician appointments, surgical procedures and emergency room visits and hospital stays. This estimate projects direct costs from hip osteoarthritis alone to exceed \$100 billion per year globally.⁵

Although we are continuing to explore the biologic basis of osteoarthritis and options for treatment, the disease is not a new one. Perhaps the earliest mention of it dates back almost three hundred years, when William Hunter published his classic work, “Of the Structure and Disease of Articulating Cartilages”, in 1743.⁶ An accomplished surgeon and avid anatomist, Hunter offered descriptions of articular cartilage, and chondral damage, that were well ahead of other studies at the time. Specifically, he mentions

stages of cartilaginous degeneration, ranging from the cartilage turning “reddish and lax”, to “raised up in blisters”, to final “bony ankylosis”, stating that “ulcerated cartilage is a troublesome disease...that, when destroyed, it is never recovered”. The earliest descriptions of generalized osteoarthritis was then published by Heberden, and then Haygarth, in the early 19th century.⁷⁻⁸ Osteoarthritis and its etiology was pondered over the course of the next 150 years, with Adams, Charcot, Cecil and Archer all making contributions to its study.⁹⁻¹¹

The 1950s saw Kellgren and Lawrence developing their radiographic grading system, which continues to be used today as a means of assessing osteoarthritis.¹² The grading scheme assigned a score of 1-4 based on the presence of joint space narrowing, osteophytes or sclerosis on radiographs. A big jump in our understanding of the disease came from Stecher, who in the 1948, introduced the idea of a post-traumatic arthritis, and a primary, idiopathic form.¹³ Over the next few decades, numerous authors, most notably Murray, Stulberg and Harris, opposed the idea of an “idiopathic” form of arthritis, demonstrating that most cases of hip osteoarthritis could be ascribed to subtle developmental deformity, be it hip dysplasia, Legg-Calvé-Perthes disease (LCP) or a mild slipped capital femoral epiphysis (SCFE).¹⁴⁻¹⁶ They argued that undiagnosed developmental deformity resulted in chondral damage over years, resulting in osteoarthritis. However, an examination of the etiology of osteoarthritis took a back seat to the flurry of activity occurring at the time around a newly developed hip prosthesis. John Charnley, a brilliant surgeon and biomedical engineer, developed a

successful technique and a low-friction total hip prosthesis, revolutionizing treatment for hip osteoarthritis.¹⁷

The concept of femoroacetabular impingement – a mechanical explanation for the development of osteoarthritis in the hip

A resurgence in literature on the etiology of these so-called idiopathic cases of hip osteoarthritis occurred in the early 2000s, after Ganz et al, in a series of papers, proposed a novel explanation for hip pain and osteoarthritis seen in adults.¹⁸⁻²²

Publishing results from their MRI studies, the group described the mechanism of impingement due to abnormal proximal femoral morphology. The first identification of impingement in the literature, however, comes from Smith-Peterson, who in 1936 described the case of a woman with a diagnosis of “bilateral intrapelvic protrusion of the acetabulum” with pain caused by the impingement of the femoral neck on the anterior acetabular margin.²³ Recognizing the source of pain led Dr. Smith-Peterson to develop an acetabular, and subsequently a femoral, “plastic procedure” - involving excision of a piece of bone off of the acetabular rim or the femoral neck, which resulted in resolution of the pain and her limp. He describes the result of his treatment on other patients, notably patients with “old slipped upper femoral epiphysis, with impingement of the projecting anterior femoral neck on the anterior acetabular margin”.

Ganz and colleagues described two primary patterns of morphology that explained the etiology of the impingement. They posited that the source of the impingement could either be from an outgrowth of bone at the femoral head-neck junction, termed a cam

deformity, or from an anatomic or functional expansion of the anterior rim of the acetabulum, termed a pincer deformity.²¹ Although a cam deformity can arise due to a number of factors, including previous fracture, subclinical SCFE, an unusually large femoral neck or some other unknown mechanism, the abnormality is readily apparent on radiographs as an aspherical femoral head. A pincer type hip, however, is a broad term referring to impingement arising from an overarching acetabulum. This encompasses morphologies like acetabular retroversion, coxa profunda, acetabulo protrusio, or generalized overcoverage. The variety of possible morphologies contributing to the impingement makes a pincer deformity harder to elucidate on radiographs. Besides describing the anatomy of these deformities, Ganz et al also proposed a corrective surgery in patients with grade I or less osteoarthritis, and published successful mid-term results on symptomatic patients.¹⁹⁻²⁰

A further study elucidated the precise patterns of damage caused by this impingement. They analyzed anteroposterior and frog-leg lateral radiographs of 244 hips, isolating 26 patients with a pure cam type deformity, and 16 patients with a pure pincer type deformity (acetabular protrusion), including only patients with grade I osteoarthritis or less to better examine the location of chondral damage.²² Careful examination of cartilage after surgical dislocation led them to identify two distinct patterns of chondral injury caused by these deformities. The cam deformity largely damaged the anterosuperior portion of the acetabular cartilage. The labrum appeared to be largely intact with minimal degenerative changes, although the junction between the labrum and acetabular cartilage was sometimes noted to be sheared off. This led them to

conclude that the mechanism of damage was the prominence at the head-neck junction entering the joint on hip flexion, applying pressure to the anterosuperior cartilage, leaving the labrum undamaged. The pincer deformity, on the other hand, causes circumferential labral damage from direct impaction of the neck against the labrum. The pincer deformity also produced a countercoup injury to the posteroinferior portion of the cartilage wall.

Defining FAI – not a trivial task

Since Ganz and his colleagues published their landmark series of papers, there has been a growing interest in FAI among orthopedists. Despite general acceptance of femoroacetabular impingement and further elucidation of its role in the development of early arthritis, the precise definition of the deformity leading to the impingement has been debated. As mentioned above, this task is slightly easier when describing a cam deformity, given its consistent radiographic appearance regardless of the source of the deformity. At a fundamental level, a cam deformity is simply an aspherical ball in a spherical cup. Formal radiographic definitions of the deformity have therefore been a measure of asphericity of the femoral head. Ganz, in his initial series of papers, proposed measuring this using a femoral head-neck offset ratio, essentially an adjusted measure of the distance between the edge of the femoral head and the femoral neck at different points circumferentially around the head.¹⁸ However, this involves significant effort, the use of an MRI with appropriate cross-sections, and is more suited to research use than clinical applications.

Notzli et al proposed the use of an alpha angle as an alternate measure of asphericity of the femoral head.²⁴ Defined on an AP plane on MRI, measuring the alpha angle first involves constructing a circle around the femoral head. A line is then drawn from the center of this circle extending through the center of the femoral neck. The angle between this line, and the point where the femoral neck “escapes” the circle encompassing the head, is termed the alpha angle. An angle greater than 55° is generally indicative of a cam deformity. However, an MRI study by Rakhra et al investigated the variation in alpha angle when measured along different radial planes around the long axis of the femur in subjects with clinically suspected FAI.²⁵ While the oblique axial plane, which would most closely resemble the plane described by Notzli, had a mean alpha angle of 53.4°, the mean maximal alpha angle in the radial planes was 70.5°. The alpha angle was consistently highest at the 2 o’clock radial plane, suggesting that these radial plane measurements might be more indicative of a cam deformity than Notzli’s original alpha angle. Studies have demonstrated the validity of using the alpha angle on plain radiographs, both on AP and frog-leg laterals, which enables the clinician to diagnose a cam impingement on routine films.²⁶⁻²⁷ However, Dudda et al. showed that a normal appearing radiograph did not necessarily preclude the presence of a cam deformity.²⁸ Indeed, an investigation comparing alpha angles measured on an AP, frog-leg lateral and Dunn view radiographs to a multiplanar MRI found that only the Dunn view had adequate reliability and accuracy in measurement.²⁹ Other recent studies have found poor reliability in the detection of a cam deformity, recommending reliance only on clinical impingement signs.³⁰⁻³¹ However, regardless of the debate about the most

appropriate plane to measure the alpha angle at, there is general consensus that the alpha angle is a reasonable indicator of a cam lesion, and increased alpha angles correlate with an increase in anterosuperior chondral damage in patients.³²

The same cannot be said of pincer impingement, however. As previously mentioned, a pincer deformity refers generically to impingement caused from an acetabular deformity versus a femoral deformity. This arises from a variety of underlying anatomy, each defined by a different radiographic sign. These include coxa profunda (defined as the presence of the acetabular fossa medial to the ilioischial line), acetabular protrusio (with the femoral head close to the ilioischial line, and the center of the femoral head medial to the anterior and posterior walls of the acetabulum), generalized overcoverage (generally defined as a center-edge angle greater than 45°), or acetabular retroversion (defined variously by the cross-over sign, ischial spine sign, or the posterior wall sign). In general, however, a pincer impingement is structurally the repeated impaction of the femoral neck against an overarching acetabulum.^a Historically, the extent of acetabular coverage is best measured using the center-edge angle of Wiberg (CE angle).

Initially developed by Gunnar Wiberg in 1939 as a way of identifying dysplastic hips, the CE angle continues to be a remarkable tool in identifying undercovered hips prone to accelerated osteoarthritis.³³ His measurements of this angle, between the line joining the center of the femoral head to the most lateral aspect of the acetabular roof and the

^a A retroverted acetabulum is a special case of this, and will be discussed in the next section. In this section, pincer impingement will refer to cases of coxa profunda, acetabular protrusio and generalized overcoverage

vertical, on a healthy population, led to the conclusion that hips with angles below 20° were abnormal. A sample of seventeen adults with dysplastic hips were followed for up to 28 years, and were all found to develop OA. In fact, the age at which the arthritis manifested in this population was directly correlated with their measured CE angle, although this finding was not replicated when subluxated hips (with a broken Shenton's line) were excluded³⁴.

Although it has been proposed that the CE angle be used as a measure of an overcovered hip, it isn't clinically apparent what threshold of CE angle should define an overcovered hip. In Wiberg's original paper, the range of CE angles in the normal population was 20° to 47° . More recently, Werner et al replicated Wiberg's study on 1635 radiographs, and found a much wider range of normal (2.1° – 57.1°)³⁵. Other studies have shown that the upper limit of the 95% confidence interval when measured on a healthy population falls around 45 - 48° ³⁶⁻³⁸. Lequesne et al used a threshold of 41° to define overcoverage, and a CE angle of 40 - 45° is generally accepted as the threshold for an overcovered hip³⁸⁻³⁹. However, this does not appear to be consistent among studies.

Additionally, the link between the presence of overcoverage and the development of osteoarthritis has not been definitively established. No longitudinal studies examining the relationship of overcoverage to the development of OA exist. This is partly because performing such a study would require following patients from early adulthood for perhaps twenty to thirty years until the development of arthritis. One study, by Bardakos et al, retrospectively measured a number of radiographic parameters,

including the CE angle and Tonnis angle, in 43 adult hips with mild or moderate osteoarthritis, looking for progression over at least 10 years.⁴⁰ They found that only the medial proximal femoral angle and the presence of a posterior-wall sign were significantly associated with progression of OA. However, since all patients presented with degrees of mild or moderate osteoarthritis, the study was unable to determine if any of the factors measured predisposed an individual to the development of arthritis.

Cross-sectional studies are easier to find, although few specifically look at the role of overcoverage to osteoarthritis. One of these, by Gosvig et al, looked at signs of FAI, including overcoverage, in 3620 individuals in Copenhagen.⁴¹ Overcoverage was defined as a CE angle greater than 45°, and osteoarthritis was defined as a joint space width less than 2 mm. They found that the presence of a high CE angle significantly elevated the risk ratio for the development of osteoarthritis. Several other studies found similar results, although most of these set out to identify the role of undercovered hips to the development of OA.^{35-36, 42} Additionally, an unintended consequence of using the CE angle as a measure of coverage is that the angle is not reliable in hips with osteoarthritis, since any joint space narrowing would proportionally alter the measured angle.

This suggests our first question:

What is the role of an overcovered hip in the development of osteoarthritis? Is there a threshold CE angle that can be identified to define a pincer deformity on the basis of the clinical probability of secondary osteoarthritis?

The duality of retroversion

The role of retroversion in the development of hip pain and osteoarthritis, however, is more defined. Siebenrock, working with Ganz, demonstrated that the presence of retroversion was associated with clinical findings of impingement and labral lesions.⁴³ Their paper also described their results from performing periacetabular osteotomies on these patients, demonstrated decreased pain and improved range of motion at the hip. Giori et al demonstrated, using radiographic projections of pelvis models, that the appearance of retroversion on an AP radiograph is generally due to a deficient posterior wall.⁴⁴ Comparing the prevalence of acetabular retroversion on groups of patients with and without idiopathic hip osteoarthritis revealed that retroversion was overrepresented in the patients with hip arthritis. Tonnis et al also demonstrated the relationship of retroversion, measured more accurately on a CT scan, to hip pain and osteoarthritis.³⁸

The mechanism of this relationship between retroversion and osteoarthritis appears to be impingement. It seems that a retroverted acetabulum would lead to a preferential overcoverage of the anterior femoral head, resulting in a pincer type impingement with repeated hip flexion. At the same time, studies have demonstrated that acetabular retroversion is also seen in dysplastic hips. Li et al analyzed 232 hips with developmental dysplasia (a CE angle less than 20°), and discovered that 17.2% were retroverted with a deficiency of coverage posteriorly as opposed to anteriolaterally, as would be expected with a dysplastic hip.⁴⁵ They suggest careful surgical planning, and surgical enhancement of posterior coverage as well as anterior coverage if retroversion is noted.

These dysplastic, retroverted hips pose an interesting question regarding the mechanism of chondral damage. As we have seen, both dysplasia and retroversion predispose an individual to the development of osteoarthritis, albeit through different mechanisms. Dysplasia results in decreased anteriolateral coverage, causing increased stresses on hip joint cartilage, causing the development of arthritis over time.

Retroversion, on the other hand, results in increased anterior coverage, resulting in impingement of the femur on the anterior labrum. It is possible, however, that these processes are in opposition with each other.

This suggests our second question:

Does retroversion cause osteoarthritis in undercovered hips? Or would the mechanism of localized anterior overcoverage secondary to retroversion only predispose individuals to arthritis in the presence of a normally covered hip?

Looking backwards – what causes these deformities in the first place?

We have so far been focused on the pathoanatomy, symptoms and outcomes of femoroacetabular impingement. In the decade since the introduction of the idea of impingement, it has been the subject of a rapidly expanding volume of the orthopedic literature. This has significantly enhanced our understanding of the problems and anatomy of impingement, and is starting to inform us about treatment for impingement and its outcomes. Particularly with cam type impingement, we are at a stage in the literature where attention is beginning to be paid to the precise etiology of the impingement, raising questions about prevention through lifestyle modification.

One hypothesis is 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 post-physeal closure, raising suspicion that the deformity arose as a result of developmental changes around the time of physeal closure.⁴⁶ Siebenbrock et al measured the location of the physeal plate in elite basketball players and controls, and found that anterosuperior extension of the physis preceded the development of a cam morphology, and was more pronounced in the players compared to controls.⁴⁷⁻⁴⁸ Presumably, repeated running and jumping activity in adolescence contributed to either eccentric loading conditions or microtrauma, resulting in gradual responsive remodeling of the physis, ultimately resulting in an aspherical head.

After physeal closure, the ability of the body to remodel diminishes drastically. However, in accordance with Wolff's law, bony architecture changes to resist compressive forces, and evidence exists that some of the asphericity of the femoral head is attributable to a lifetime of eccentric forces on the femur, resulting in a degenerative cam deformity.⁴⁹ The pathophysiology of this post-developmental cam deformity has multiple proposed explanations, including decreased hydrostatic pressure at the joint margin, impaction into the acetabular rim and subsequent remodeling or shaping of the head over years of motion in the flexion-extension plane.⁵⁰

At the same time, genetic factors have been known to contribute as well. Pollard et al examined the prevalence of cam deformities in siblings of patients with symptomatic FAI, noting siblings were 2.8 times more likely to exhibit an asymptomatic cam

deformity when compared to controls.⁵¹ Additionally, they found numerous instances of erosions along the head-neck junction in young cam hips, leading them to believe that reactive bone formation to unusual stresses led to exacerbation of a congenital or genetically determined cam deformity, explaining the differing degrees of symptomatology among siblings. However, while powerful, this study could not adequately parse out whether the source of these similarities in morphology between siblings were purely genetic, or the product of similar activity levels and environmental factors stemming from a shared childhood.

Looking at the evolutionary basis of human osteology offers much insight into the development of the deformity, although it has been largely ignored by orthopedists. Much of the work on this comes from biologic anthropologists, particularly the works of Lovejoy et al.⁵²⁻⁵³ The current design of the human hip developed first as an adaptation to obligatory bipedalism and the development of the “running ape”. Later adaptations to the pelvis, particularly in women, arose from a tendency toward the delivery of babies with larger brains, and consequently increasingly dangerous labor and birth. Hogervorst et al examined the morphology of mammalian hips and outlined two broad designs that described all the hips studied.⁵⁴ One, termed coxa recta is found in most mammals, and demonstrates a distinct aspherical section at the femoral head-neck junction, and conferring an increase in stability but decreased range of motion. The second, termed coxa rotunda, found in swimmers and climbers including apes, demonstrates the more familiar round femoral head with pronounced concavity at the head-neck junction. This provided these mammals with greatly increased range of

motion, while sacrificing stability. Although human hips broadly fall into this category, almost 20% of asymptomatic hips demonstrate morphology closer to coxa recta, or an aspherical femoral head.⁵⁵ This appears to be a case of convergent evolution explained by the increased need for stability with running and bipedalism. Facultative bipeds, such as Apes, have never been found to have a cam deformity.

This raises our final question:

What is the antiquity of the cam deformity? Did it arise from an evolutionary shift from facultative bipedalism to obligatory bipedalism, from a need for increased stability at the cost of range of motion? Or is it a more modern injury, arising as a consequence of current day activity and behavior?

Chapter 2 - Specific Aims and Hypotheses:

We aim to explore the above presented questions related to femoroacetabular impingement through this study, in the hope of furthering the already expansive literature on the topic. This section presents the three aforementioned questions, along with our approach to solving the problem and the associated hypothesis.

***Specific aim 1:** What is the role of an overcovered hip in the development of osteoarthritis? Is there a threshold CE angle that can be identified to define a pincer deformity on the basis of the clinical probability of secondary osteoarthritis?*

The best way to answer this questions would probably be to isolate a population of healthy adults with overcovered hips, following them out to the development of arthritis. Given that the idea of pincer impingement as an explanation for cases of “idiopathic” osteoarthritis is only about a decade old, no such longitudinal studies exist. Additionally, given that the CE angle is inaccurate when measured on hips with any osteoarthritis, cross-sectional studies utilizing the CE angle are hard to interpret as well. We sought to look at the role of overcoverage in the development of accelerated OA of the hip, and to identify this threshold of overcoverage, by looking at the problem “backwards”, so to speak. We looked at hip radiographs, taken for any reason, in patients below the age of 35 that had no radiographic signs of OA, to catalog the normal range of CE angles in our study population. We then compared these to radiographs of OA-free hips from patients above 65 years of age, to determine the range of CE angles in hips that “make it” to 65 without showing signs of degeneration. We hypothesized that

we would see a narrowing of the range of CE angles in the older group versus the younger, due to a “drop out” in hips at the extremes of acetabular coverage due to the development of accelerated OA. We sought to use comparisons of the two groups to determine the CE angle threshold above which a hip would be likely to undergo degeneration, enabling better clinical decisions regarding early intervention.

Specific Aim 2: *In the presence of both dysplasia and retroversion, would the presence of increased anterior coverage decrease stresses on an otherwise undercovered hip? Alternatively, are the mechanisms distinct and not completely antagonistic, resulting in hips that do even worse over time?*

Our approach to this question used a method similar to our previous strategy. We looked at a sample of hips with no signs of osteoarthritis in patients under the age of 35, and patients over the age of 65. Hips were carefully chosen to be orthograde, demonstrating an AP view with the measured distance between the pubic symphysis and the coccyx falling between 1 and 3 cm. Hips were studied for the presence of signs of retroversion, the CE angle was measured. This enabled us to compare the subset of retroverted hips in the two patient populations. Additionally, this also enabled us to determine if the subset of dysplastic, retroverted hips were over or underrepresented between the two populations. We hypothesized that the anterior overcoverage secondary to retroversion would be protective against the effects of increased stress due to undercoverage in dysplastic hips.

Specific Aim 3: *What is the antiquity of the cam deformity? Did it arise from an evolutionary shift from facultative bipedalism to obligatory bipedalism, from a need for increased stability at the cost of range of motion? Or is it a more modern injury, arising as a consequence of current day activity and behavior?*

For our study, we sought to examine the antiquity of the cam deformity, by analyzing the prevalence of abnormal proximal femoral morphology in early humans. We chose to study proximal femoral morphology from the Libben Osteological collection, a set of 8th-11th century AD human bones from a single, homogenous population of hunter-gatherers. Comparing this morphology to data on modern humans, obtained from the Hamann-Todd collection, will enable us to determine if the cam deformity is a product of an evolutionary shift to bipedalism, or a result of modern behaviors.

The Libben site is a Late Woodland ossuary containing the remains of 1327 individuals located in Ottawa county, Iowa.⁵⁶ The population represents approximately 10 generations of a prehistoric hunter-gatherer tribe, living in the Great Black swamp between the 8th and 11th centuries AD.⁵⁷ Libben represents the biggest, most-complete, single-occupation cemetery in the Eastern Woodlands. This constitutes the most extensively studied prehistoric collection in North America, allowing us to identify differences in behavior between this population and modern humans.

Libben represents a single, homogenous, hunting-fishing-gathering village that was continually occupied for approximately 300 years. The population was predominantly a trap and weir economy. The diet consisted largely of fish caught in nearby streams,

small mammals such as muskrat trapped in the neighboring swamp, and occasionally fowl and deer. Agriculture, in the form of cultivated maize and shellfish, was present, although played a miniscule role in the population. Daily life involved hard work in the form of trapping game and collecting firewood, involving extended walking and carrying heavy loads. Village size was quite small due to limitations on resources and early deaths, generally only encompassing two generations, and required all able-bodied people to contribute to work in the community. Nutrition was likely limited, and restricted to one meal a day, with prolonged rest periods involving squatting and sleeping.

We aimed to analyze how differences in day to day behavior between ancient and modern humans dictates the shape of the human hip, particularly hypothesizing the development of the cam deformity as a product of the demands of modern life rather than being derived from the need for increased stability with the evolution of obligatory bipedalism.

Given the disparate nature of the questions being answered in these studies, the following chapters will be organized by specific aim, presenting the methods, results and a discussion of research method limitations for each question in each chapter. The final chapter will revisit our conclusions and discuss the results in the context of existing literature.

Chapter 3 – The Effect of Overcoverage on the Development of Osteoarthritis

Methods

After obtaining appropriate approval from our institutional review board, we obtained all AP pelvis x-rays taken in patients under the age of 35, and over 65, at our institution, a university hospital in the North-Eastern United States. Radiographs were taken between 2003 and 2013, and were read as “unremarkable” for signs of osteoarthritis per the radiologist report. 5145 radiographs from the older age group, and 1397 radiographs from the younger group were obtained, and the radiologist reports and charts were examined to determine inclusion in the study. In order to ensure consistency, radiographs were included only if the radiographic report explicitly commented on the absence of radiographic signs of arthritis or degeneration. Exclusion criteria included the presence of systemic conditions affecting joint integrity (such as rheumatoid arthritis, lupus, gout etc.), the presence of fractures involving the proximal femur or the acetabular roof, other identified hip pathology or bilateral arthroplasties. The images that met these criteria included considerably more females than males (approximately 67% female), and the authors were concerned with generalizability of the sample population. Consequently, images were sorted by gender, and a random sample of 125 images were selected from each gender in both age groups. The CE angles in these images were measured using the method outlined below, and compared to ensure that angles were not different between genders within each age group (t-test, $p > 0.05$). Once confirmed, an additional 250 images were randomly selected from each

age group, irrespective of gender, giving us 500 images in total for both the younger and the older cohort. Of these, a further 54 images in the older age group and 23 images in the younger age group were excluded for reasons of poor image quality or because they were repeat images on the same patient. In the case of these repeat x-rays, only the most recent radiograph was included in the sample.



Figure 3-1: Method used in measuring CE angles. Circles are drawn encircling both femoral heads, and a line is drawn through their centres. The CE angle is between the perpendicular to this line and the line connecting the center of the femoral head to the lateral edge of the acetabular cup. In case bilateral hips are not usable, the ischial tuberosity is used for alignment instead.

The remaining images (446 patients, 755 hips in the older group and 477 patients, 932 hips in the younger group) underwent measurements of their CE angles using custom software coded on MATLAB (Mathworks Inc, MA). Circles were drawn encompassing the femoral heads, and a line was drawn connecting their centers. In case of hips with

opposite side osteoarthritis, or arthroplasty, a line was drawn joining the base of the ischial tuberosities. CE angle was measured between the perpendicular to this line, and the line connecting the center of the femoral head to the lateral edge of the acetabular cup, as shown in Figure 3-1.

Statistical analysis was performed using SPSS 20.0 (IBM Corporation, NY). Normality of the distribution was assessed using the Shapiro-Wilk test. Average, standard deviation, range and skewness were calculated to determine the distribution of CE angles in the hips in each group. The ten most overcovered hips in each group, along with hips with apparent signs of degeneration, were reviewed by a board certified radiologist to confirm the absence of signs of arthritis or confounding factors like acetabular protrusion.

A random sample of twenty hips were re-measured using the program, and manually by a board certified orthopedic surgeon to assess intraobserver and interobserver agreement, using the Intraclass Correlation Coefficient (ICC) and Pearson's correlation coefficient (r). A level of 0.8 for ICC and 0.75 for Pearson's coefficient was defined as excellent agreement. Comparisons between CE angle means (between age groups, by gender, and by laterality) were performed using the t-test for independent samples, and comparisons of proportions (hips in each age group falling under different CE angle ranges, Table 3-2) were done using Fisher's exact test. A two-tailed p-value of 0.05 was defined as the threshold for significance.

Results

Table 3-1 – Descriptive data					
Younger group	Freq	%	Older group	Freq	%
Age			Age		
20 yrs and below	72	15.1	65-74 yrs	218	48.9
21-25 yrs	114	23.9	75-84 yrs	152	34.1
26-30 yrs	148	31.0	85-94 yrs	73	16.3
31-35 yrs	143	30.0	95 yrs and up	3	0.7
Gender			Gender		
Male	207	43.4	Male	190	42.6
Female	270	56.6	Female	256	57.4
Chief complaint			Chief complaint		
Hip pain	284	59.5	Hip pain	301	67.5
Trauma	139	29.1	Trauma	73	16.3
Post-op	19	4.0	Post-op	60	13.4
Other	35	7.4	Other	12	2.8
Side			Side		
Left	8	1.7	Left	75	16.8
Right	14	2.9	Right	62	13.9
Both	455	95.4	Both	309	69.3
Total	477	100.0%		446	100.0%

Table 3-1: Descriptive data of both populations.

446 (755 patent hips) images from the older group were used for the analysis. There were 256 females (57.4%) and 190 males (42.6%). Patient ages ranged from 65 to 99, with a median age of 76 years. Most images were taken for complaints of hip pain (67.5%), followed by trauma (16.3%) and post-op films (13.4%). 477 images (932 patent hips) from the younger group were similarly analyzed. This group consisted of 270 females (56.6%) and 207 males (43.4%), with a median age of 27 years (range 18-34 years). Once again, most images were taken for complaints of hip pain (59.5%), although a greater proportion of images were taken after trauma (29.1%). Post-operative films

only contributed to 4.0% of images in this age group. Table 3-1 outlines descriptive statistics about the sample population. The Shapiro-Wilk test confirmed the normality of the distribution for both groups ($p = 0.031$ for the older, $p = 0.0001$ for the younger).

Intraobserver and interobserver correlation was excellent, demonstrating the validity of the software. Intraobserver readings on twenty randomly selected hips showed an ICC of 0.968 and a Pearson's coefficient of 0.951. Interobserver readings on these same hips, done manually on physical radiographs by the PI, D.C., a board certified orthopedic surgeon, showed an ICC of 0.898 and a Pearson's coefficient of 0.808.

The average CE angle in the younger group was 34.90° with a standard deviation of 6.79° , while the mean CE angle in the older group was 36.96° with a standard deviation of 6.93° ($p < 0.0001$). CE angles ranged between -4° and 60° in the younger group and between 14° and 57° in the older group. The most frequent angle (after rounding to the nearest integer) in both populations was 35° . Figure 3-2a and 3-2b shows the histogram of the two populations for comparison.

Average CE angle did not differ by gender in either population ($p = 0.096$ in the older group, $p = 0.624$ in the younger group). However, average CE angle was statistically different in both populations when compared by side (Older group - 37.73° for left hips vs 36.15° for right hips, $p = 0.002$; Younger group - 35.64° for left hips vs 34.16° for right hips, $p = 0.001$).

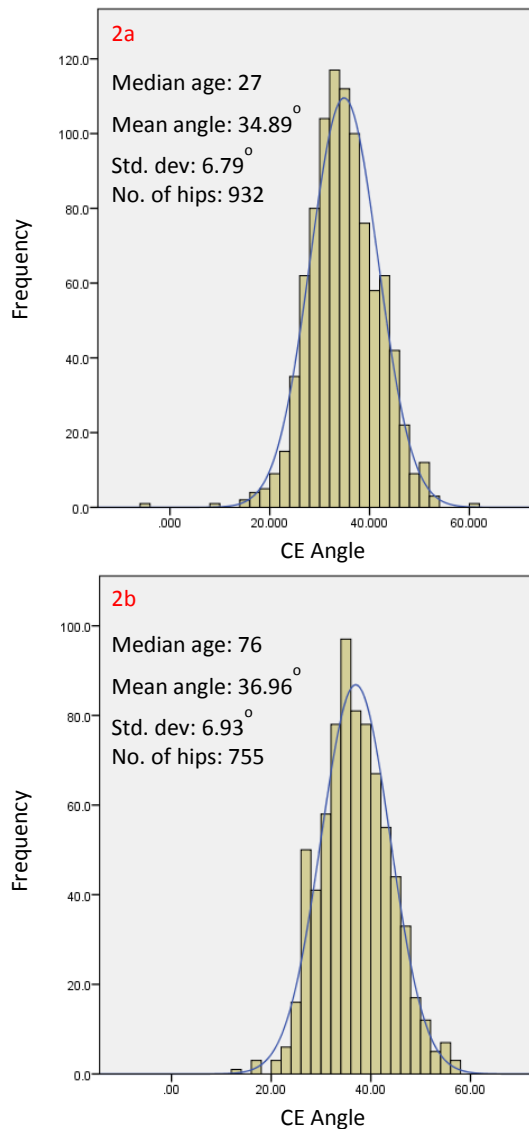


Figure 3-2: Histogram of calculated CE angles, with normal curve for the younger (2a) and older (2b) study populations.

In order to observe the symmetry of the two distributions, hips in both groups were sorted by CE angle. The percentage of hips in each category as a proportion of total number of possible hips (954 in the younger group, 892 in the older group), was compared between age groups in order to study the symmetry of the two distributions, shown in Table 3-2.

	<= 20°	21 – 34°	35 – 45°	> 45°
Number of hips in younger cohort (% of total)	16 (1.7%)	446 (46.8%)	423 (44.3%)	72 (7.5%)
Number of hips in older cohort (% of total)	5 (0.6%)	268 (30.0%)	397 (44.5%)	112 (12.5%)
p value	0.025*	0.0001*	0.96	0.0003*

Table 3-2: Number of hips in both age groups, sorted by Wiberg CE Angle in order to study the symmetry of the distributions. P-values were calculated using Fischer's exact test as a proportion of total hips. Note the underrepresentation of the older cohort among hips with CE angles $\leq 20^\circ$ and between 21 and 34° .

Discussion

It is generally accepted that acetabular dysplasia, or undercoverage, leads to accelerated OA. The opposite end of the spectrum, acetabular overcoverage, has only recently received attention, with the concept of femoroacetabular impingement (FAI).²¹

FAI is generally classified into cam-type (caused by a non-spherical femoral head) or pincer-type impingement (caused by excessive acetabular coverage).²² On radiographs, the cam-type deformity is defined using the alpha angle with angles above 50° considered pathologic.⁵⁸

No similar consensus measure is defined for pincer-type impingement, although a CE angle greater than 40° - 45° , or a Tonnis angle less than 0° , is sometimes found in the literature.^{38,59} This could be because a pincer-type impingement could be due to a number of morphological patterns, each defined by a different radiographical finding. This includes coxa profunda, acetabular retroversion or generalized overcoverage. We were particularly interested in the role of the CE angle as a marker for overcoverage.

We could find no longitudinal studies that looked at the role of acetabular overcoverage, and in particular those manifesting a high CE angle, in the development of osteoarthritis. One study, by Bardakos et al, retrospectively measured a number of radiographic parameters, including the CE angle and Tonnis angle, in 43 adult hips with mild or moderate osteoarthritis, looking for progression over at least 10 years.⁴⁰ In this study, increased CE angle was found to not be correlated with the progression of OA. In fact, only the medial proximal femoral angle and the presence of a posterior-wall sign were significantly associated with progression of OA. However, all patients enrolled presented with mild or moderate osteoarthritis, and it is unclear if any of the factors measured predisposed an individual to the development of arthritis in the first place.

Cross-sectional studies are easier to find, although few specifically look at the role of overcoverage to osteoarthritis. One of these, by Gosvig et al, looked at signs of FAI, including overcoverage, in 3620 individuals in Copenhagen.⁴¹ Overcoverage was defined as a CE angle greater than 45°, and osteoarthritis was defined as a joint space width less than 2 mm. They found that the presence of a high CE angle significantly elevated the risk ratio for the development of osteoarthritis. Several other studies found similar results, although most of these studies were set up to identify the role of undercovered hips to the development of OA.^{21, 36, 42}

Considering a longitudinal study would require following patients with overcovered hips perhaps 20-30 years to the development of arthritis, we sought to look at a cross-section of hips that survived to sixty-five without arthritis, and compare them to a cross-section of healthy hips in young adults, to observe the symmetry of overcovered hips

between the two populations. In general, the distribution of angles in the younger sample matched other studies looking at similarly aged populations.^{33,35} We found that the average CE angle increased by about two degrees (34.90° to 36.96°) in the older population compared to the younger population. Additionally, the range of angles in the younger hips was much wider than in the older hips (-4° to 60° compared to 14° to 57°). This appears to suggest that hips at the extremes of acetabular overcoverage as well as acetabular undercoverage, drop out of the population before old age. Presumably, they develop early arthritis, with dysplastic hips being particularly affected, causing a narrowing of the range of CE angles and a concomitant rise in the mean CE angle in the older patients.

Unsurprisingly, when we compared the symmetry of distribution of angles in the young and older populations, we found that hips with CE angles less than or equal to 20° do not do well over time. 16 hips in the younger population fell into this category, compared to only 5 in the older group ($p=0.025$). Additionally, the most dysplastic hips in the younger group had CE angles ranging from -4° to 10° . As expected angles under 10° were not seen in the older group. However, a few hips with CE angles less than 20° survived to the age of 65 with no signs of OA. Some examples of these hips are shown in Figure 3-3. The authors consider the endurance of these hips interesting, but probably outside the bounds of reasonable expectation.

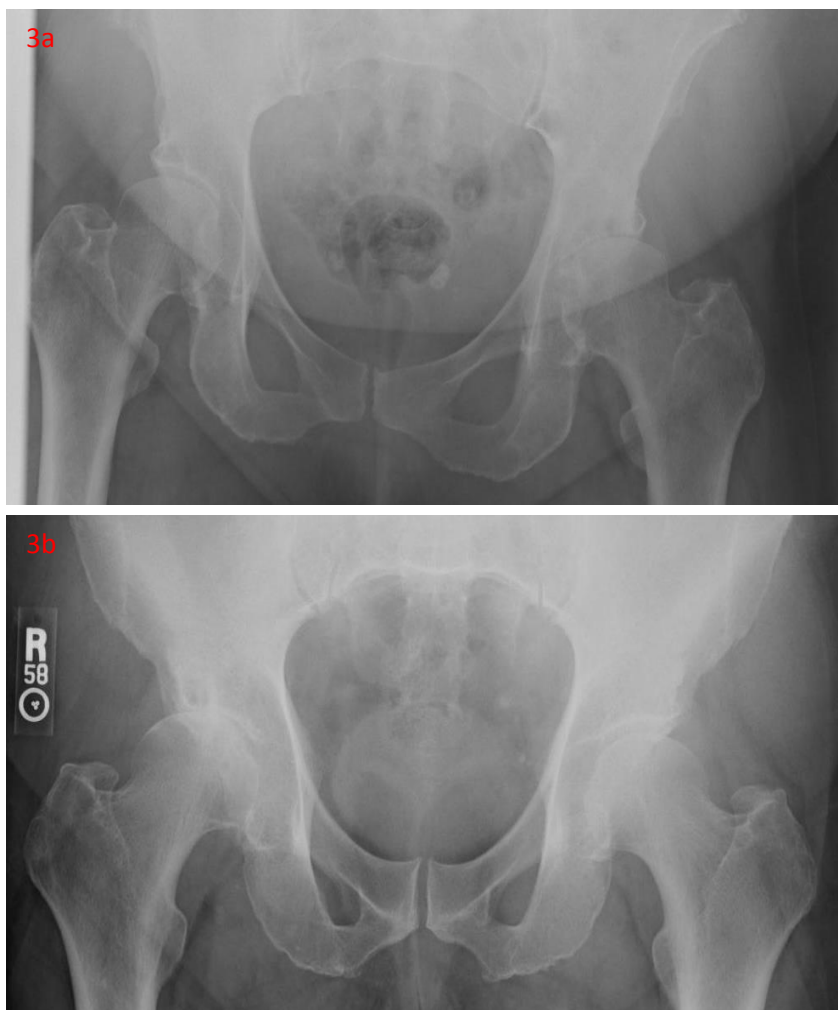


Figure 3-3a, b: Examples of hips from the sample older population exhibiting acetabular dysplasia but no evidence of osteoarthritis. 3a is from a 68 y/o female with notable arthritis on the L, and a CE angle of 17.54° on the R. 3b is from a 71 y/o male with pronounced R sided OA, and a CE angle of 17.66° on the L.

What is more surprising to note, is that a smaller, but still significant, proportion of hips with CE angles between 20° and 35° also seem to be significantly underrepresented in the older patients (Table 3-2, $p < 0.0001$). What causes the development of arthritis in this group is unclear, and beyond the scope of this study. It is possible that there is an inherent cartilage defect present to varying levels in the normal population that causes susceptible joints to develop OA when exposed to otherwise normal stresses. It seems

that hips with angles between 35° and 45°, by distributing the stresses over a larger area and decreasing pressure on the acetabular chondrum, avoid this fate; their distribution was not different between the two age groups ($p=0.96$).

It is also interesting to note that based on our data, it seems that acetabular overcoverage does not lead to accelerated OA in the general population. In fact, there is actually an overrepresentation of overcovered hips in the older age group. This is quite unexpected, as it has been largely accepted that overcoverage causes chondral damage due to impact with the acetabular abutment. Our results, however, show that a significant number of hips exist in the older age group with a CE angle greater than 45°. Figure 3-4 shows a sample of these overcovered hips that, despite being considered substantially overcovered by conventional wisdom, remain arthritis-free well into advanced age.

It is possible that only patients with susceptible cartilage or increased stresses at the hip joint are at-risk to develop OA, regardless of the level of overcoverage. Additionally, it is possible that proximal femoral morphology may have played a mitigating role in the development of signs of impingement, and subsequent arthritis. An anteverted or more varus femoral neck may perhaps be able to compensate for an overcovered acetabulum, resulting in diminished or no symptoms of impingement in this group of patients. Unlike hip dysplasia, it would appear that there is no threshold value of acetabular coverage above which hip degeneration is likely to occur. The decision to operate on hips with suspected pincer impingement is likely to rely more on a thorough clinical examination

and the use of functional assessment scores on a case-by-case basis rather than any one particular radiographic marker.^{58,60}

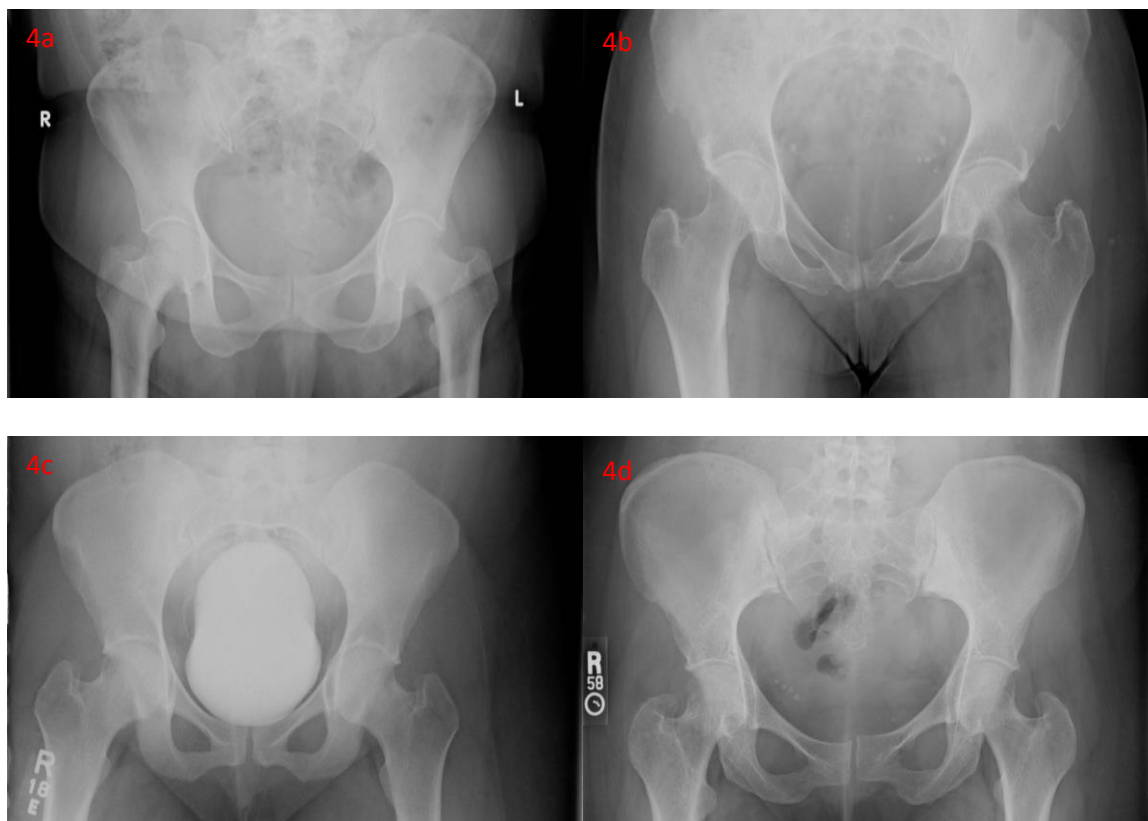


Figure 3-4 a-d: Examples of hips from the old and young sample population exhibiting acetabular overcoverage but no evidence of osteoarthritis. 4a is from a 65 y/o female, with CE angles of 52.54° on the L, and 46.67° on the R. 4b is from a 73 y/o female, with CE angles of 56.41° on the L, and 52.68° on the R. 4c is from a 25 y/o female, with CE angles of 60.18° on the L and 50.96° on the R. 4d is from a 32 y/o female, with CE angles of 52.95° on the L and 51.80° on the R.

Our study has some limitations. As previously mentioned, accurately assessing the threshold of overcoverage that would predispose an individual to OA would require a longitudinal study, with follow up to at least sixty-five or the development of OA. Our study was cross-sectional, but perhaps provides a guideline going forward, as we await the results of long term studies.

Secondly, although hips were only included if they showed no signs of chondral damage, most radiographs in our sample were taken for complaints of hip pain. It is consequently possible that our sample does not accurately represent the general population in terms of the range of hip morphology. However, this is unlikely to be the case, given that the distributions of angles in the younger population closely matched data seen in other studies involving healthy subjects in a similar age group.

Finally, we only looked at a radiographic indicator of overcoverage, and not clinical symptoms. Previous studies defining the threshold of overcoverage as a CE angle greater than 40° - 45° have been based on the presence of clinical signs of FAI.³⁹ Our study looked at the CE angle in isolation, and found that there is no simple threshold of acetabular overcoverage above which accelerated OA was likely. However, it is important to note that the multiple morphologies associated with a pincer-type impingement mean that this conclusion does not completely rule out the usefulness of the CE angle in identifying at-risk hips. Coupled with clinical judgment, a patient's functional status and other radiographic indicators, it could still hold potential in predicting the risk of OA supervening in any given individual with overcovered hips.

Chapter 4 – Is Undercoverage Protective against the Development of Osteoarthritis in a Retroverted Hip?

Methods: After institutional approval, we analyzed the set of radiographs previously used for specific aim 1. These were hips that were described by the radiologist read as being “unremarkable”, taken for any reason, in patients below 35 and above 65 years of age. Signs of retroversion, particularly the cross-over sign, is difficult to appreciate on poor quality images. In order to ensure accuracy, images were screened for appropriate image quality. Additionally, the radiographic signs of retroversion are dependent upon proper pelvic positioning, and consequently, images were only included with the absence of pelvic tilt, with the distance between the pubic symphysis and coccyx measured to be between 1 and 3 cm.

In all, 256 radiographs met the above criteria, 130 in patients over 65, and 126 in patients under 35. The readers were blind to the order of the images, and which group the image came from. Images were read on high-resolution monitors configured specifically for radiology use. Two board certified orthopedic surgeons, one board certified musculoskeletal radiologist and a fourth year medical student read and interpreted the images together, identifying the presence of signs of retroversion through consensus. Each hip was approached independently, and analyzed for the presence of the cross-over sign and the ischial spine sign.

The cross-over sign appears when the posterior wall of the acetabulum crosses over the anterior wall of the acetabulum on an AP projection. This has been validated previously as a reliable radiographic measure of retroversion. The ischial spine sign is the

appearance of the ischial spine within the pelvic inlet, when observed on an AP projection. This has also been validated as an indicator of retroversion, and is sometimes preferred since it is markedly easier to appreciate when compared to the cross-over sign. Figure 4-1 demonstrates the cross-over and ischial spine signs on a standard AP of the pelvis.

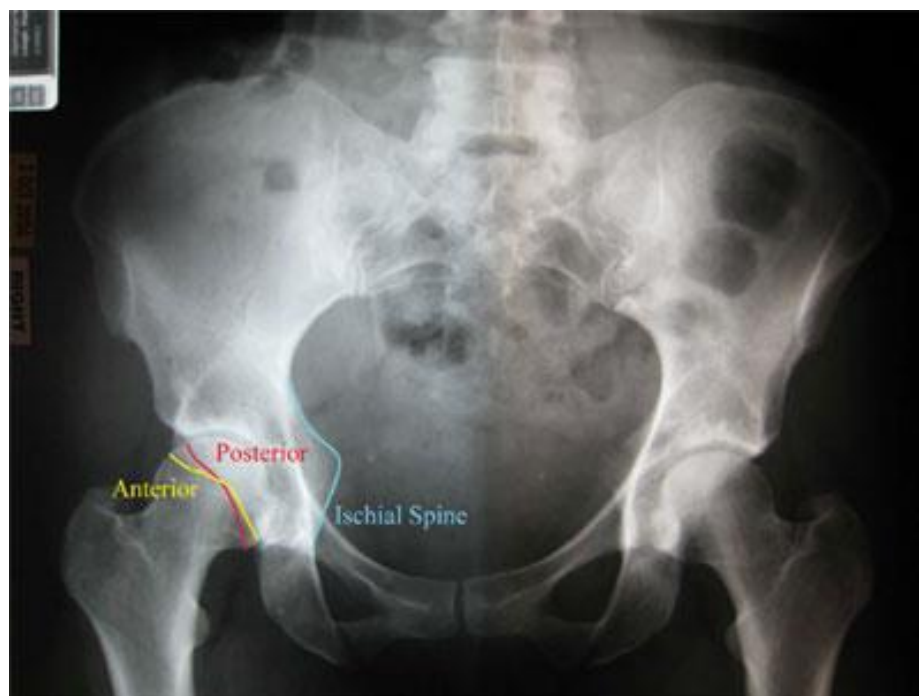


Figure 4-1: Figure demonstrating the cross-over sign and ischial spine sign on a retroverted hip. Image obtained from <http://www.carlosguanchemd.com/wp-content/uploads/2012/08/hip-x-ray.jpg>, retrieved December 12th, 2014.

Once the images were graded, results were sorted into the appropriate age groups. All statistical analyses were performed using SPSS 20.0 (IBM Corporation, MA). The proportion of hips demonstrating signs of retroversion between the groups were analyzed using Fischer's exact test. Tests studied the proportion of hips between the two groups that showed a cross-over sign on either side, a cross-over sign bilaterally, an ischial spine sign on any hip, ischial spine signs bilaterally, both signs of retroversion

unilaterally or bilaterally, and any sign of retroversion on any hip. Additionally, since these hips were previously used for specific aim 1, all hips used had an associated CE angle measurement. We compared the proportion of hips that showed signs of retroversion based on the above mentioned criteria among groups of hips that were undercovered (CE angle < 25) or overcovered (CE angle > 45), to determine if retroversion had a protective role in preventing osteoarthritis in dysplastic hips. Proportions were compared using Fischer's exact test. The level of significance was placed at a two-tailed p value less than 0.05.

Results:

There were 256 images across both groups (130 in the older and 126 in the younger). In all, 478 hips were analyzed (239 left, 239 right). Table 4-1 illustrates the differences in the prevalence of signs of retroversion between the two groups studied. As expected, all variables studied were significantly different between the two groups.

	Young hips (Age < 35 years)	Old hips (Age > 65 years)	p-value
Hips with positive cross-over sign	137 (54.4%)	72 (30.5%)	<0.001
Hips with positive ischial spine sign	116 (46.0%)	67 (26.5%)	<0.001
Hips with positive cross-over signs and positive ischial spine signs	100 (39.7%)	45 (19.1%)	<0.001
Hips with at least one positive retroversion sign	153 (60.7%)	90 (38.3%)	<0.001

Table 4-1: Number and percentage of hips with a cross-over sign, ischial spine sign, both, or either sign present in the younger and older populations, with differences between the two assessed using Fischer's exact test. Notice the high prevalence of signs of retroversion in the healthy population, and that the presence of these signs are significantly different between populations.

Our interest, however, was in discovering if the effects of retroversion could be mitigated by a dysplastic hip. Although conventional definitions of hip dysplasia refer to a CE angle less than 20°, with a CE angle less than 25° described as borderline, we found that using this as our threshold would lead to an underpowered analysis (n=3 in the older group, n=12 in the younger). Therefore, a threshold of 30° was used instead. This allowed for an adequately powered analysis for both groups (hips with a CE angle less than or equal to 30°, and greater than 30°). Table 4-2 and Table 4-3 demonstrate the prevalence of retroverted hips in each of these groups, respectively. In general, hips that were undercovered by our definition showed no difference in the prevalence of retroversion signs between the older and younger groups. When only hips with a CE angle greater than 30° were included in the analysis, all measures of retroversion were underrepresented in the older group.

Table 4-2: Comparison of the prevalence of retroversion signs among older and younger populations in hips with a CE angle less than or equal to 30°

	Young hips (Age < 35 years)	Old hips (Age > 65 years)	p-value
Hips with positive cross-over sign	28 (41.2%)	8 (34.8%)	0.631
Hips with positive ischial spine sign	20 (29.4%)	8 (33.3%)	0.798
Hips with positive cross-over signs and positive ischial spine signs	16 (23.5%)	3 (13.0%)	0.381
Hips with at least one positive retroversion sign	32 (47.1%)	12 (52.2%)	0.810

Table 4-2: Number and percentage of undercovered hips (with a CE angle less than or equal to 30°) with a cross-over sign, ischial spine sign, both, or either sign present in the younger and older populations. Differences between the two were assessed using fisher's exact test. None of the tested variables were found to be significantly different between the two populations.

Table 4-3: Comparison of the prevalence of retroversion signs among older and younger populations in hips with a CE angle greater than 30°

	Young hips (Age < 35 years)	Old hips (Age > 65 years)	p-value
Hips with positive cross-over sign	108 (59.0%)	60 (30.9%)	<0.001
Hips with positive ischial spine sign	96 (52.5%)	52 (26.5%)	<0.001
Hips with positive cross-over signs and positive ischial spine signs	84 (45.9%)	39 (20.2%)	<0.001
Hips with at least one positive retroversion sign	120 (65.6%)	72 (37.3%)	<0.001

Table 4-3: Number and percentage of normally covered hips (with a CE angle greater than 30°) with a cross-over sign, ischial spine sign, both, or either sign present in the younger and older populations. Differences between the two were assessed using fisher's exact test. As opposed to the undercovered hips, all of the tested variables were found to be significantly different between the two populations.

Discussion

Although femoroacetabular impingement has received a lot of attention in the literature in the past decade, studies on the long term clinical effects of a pincer deformity have been slow to appear. This is partly because pincer impingement is a loosely defined collection of anatomical deformities arising from the acetabulum as opposed to the femur. The general concept relates that a flexing femur would impinge on an overarching acetabulum, causing labral damage and the eventual development of osteoarthritis. This encompasses a broad range of morphologies including generalized overcoverage, acetabular protrusio, coxa profunda and acetabular retroversion.

Among these, the role of retroversion in predisposing individuals to the development of hip osteoarthritis has been well established. Siebenrock analyzed hips for the presence of retroversion on MRI, demonstrating that the presence of retroversion was associated with labral damage as a consequence of impingement.⁴³ Tonnis later demonstrated through a cross-sectional study that hips with osteoarthritis had an increased prevalence of retroversion compared to hips without arthritis.³⁸ Mechanistically, retroversion is unique in that the principal mechanism of overcoverage is an angulation of the acetabulum along the sagittal plane. This results in localized anterior extension of the acetabulum rather than an anatomically enlarged acetabulum causing the impingement.

We questioned if an undercovered hip would offer some protection against the effects of retroversion on the development of arthritis. We hypothesized that an acetabulum covering a smaller area of the femoral head would limit the amount of anterior overcoverage resulting from retroversion, causing decreased impingement and labral damage. We isolated groups of AP pelvis radiographs without radiological evidence of osteoarthritis in patients over the age of 65 and below the age of 35. These radiographs were selected to be orthograde, enabling us to accurately identify the presence of retroversion. The CE angle of all hips was measured, and hips with angles less than or equal to 30° , and greater than 30° , were separated into groups.

In the latter group, the prevalence of retroversion was significantly different between the older and younger groups. There was a significantly higher proportion of retroverted hips in the younger population compared to the older population. Presumably, these

retroverted hips develop early arthritis, and are underrepresented in the older group.

This is as expected based on previous studies, confirming that retroversion does appear to predispose individuals to the development of arthritis, at least in hips with a CE angle greater than 30°.

In undercovered hips, defined as hips with a CE angle less than or equal to 30°, the prevalence of retroversion was not significantly different between the older and younger groups. This is consistent with our hypothesis, and it appears that retroverted hips with CE angles less than 30° are equally represented in both groups. It seems that the previously accepted role of retroversion to the development of osteoarthritis needs some revision. Retroversion predisposes an individual to the development of early osteoarthritis, provided that the hip has a CE angle greater than 30°. Since the average CE angle in the healthy population is approximately 35°, this would encompass most individuals. However, for the few individuals with undercovered hips, i.e. a CE angle less than 30°, it would seem that the presence of retroversion is not a definite indicator of the early osteoarthritis in the future.

We set out specifically to analyze the interaction of retroversion in dysplastic hips and borderline dysplastic hips. However, we were limited in this since our study was inadequately powered to look at the subset of hips with CE angles less than 20° or 25°.

We were also limited by the reliability of the signs of retroversion we used, since we were examining plain radiographs as opposed to MRI or CT. Both the cross-over sign and the ischial spine sign has been previously validated as indicators of retroversion.

However, other studies have contested this, and a higher imaging modality would undoubtedly have provided a more accurate measure of the presence of retroversion.^{61,62} In order to improve the accuracy of our findings, we selected for orthograde, good quality radiographs with minimal pelvic tilt. Additionally, images were read by two board certified orthopedic surgeons and one board certified musculoskeletal radiologist, with the presence of signs of retroversion confirmed by consensus.

One other disadvantage of using radiographs is that we were unable to measure or identify changes in proximal femoral morphology that might contribute to the development of impingement and subsequently, osteoarthritis. As in the previous specific aim, a more anteverted femur may mitigate the effect of a retroverted acetabulum, preventing impaction of the femoral neck against the acetabular rim on impaction. This was beyond the scope of this study, and our results demonstrating a relationship between acetabular retroversion and dysplasia are still valid.

Finally, although our results are convincing, it only demonstrates the existence of interaction between retroversion and acetabular coverage. We can only speculate on the mechanistic reasons for this interaction. Further study analyzing labral wear patterns, correlating them with the degree of undercoverage and retroversion, would be needed to fully identify the precise mechanical forces at work.

Chapter 5 – The Antiquity of the Cam Deformity

Methods

We analyzed 1372 individuals from the Libben osteological collection, described earlier. The 1372 individuals ranged in age from the first trimester of life to over 70 years of age. Among these skeletons, 710 were found to be skeletally mature. We excluded any femora with grossly visible abnormality or deformity, such as osteonecrosis, osteoarthritis, healed fractures etc. This finally yielded 175 skeletons with at least one femur in a condition appropriate for this study. Table 5-1 displays the distribution of age and sex in the study population.

Table 5-1: Demographic data in the study population	
Sex:	
Male	83 (47.4%)
Female	63 (36.0%)
Unknown	29 (16.6%)
Age:	
17-25 years	38 (24.1%)
26-35 years	66 (41.8%)
36-45 years	45 (28.5%)
46-55 years	9 (5.7%)
Laterality:	
Right	45 (25.7%)
Left	56 (32.0%)
Both	74 (42.3%)
Total:	175

Table 5-1: Demographic data outlining the sex, age and laterality of femurs obtained from the Libben collection and included in the study.

Each femur was digitally photographed in two positions – AP and axial, as described by Toogood et al.⁶³ A total of four views were generated for each femur in order to fully elucidate all the required measurements. Specifically, measured variables included the

true and apparent neck-shaft angle (NSA), the version angle and the inclination angle, and the alpha and beta angles.

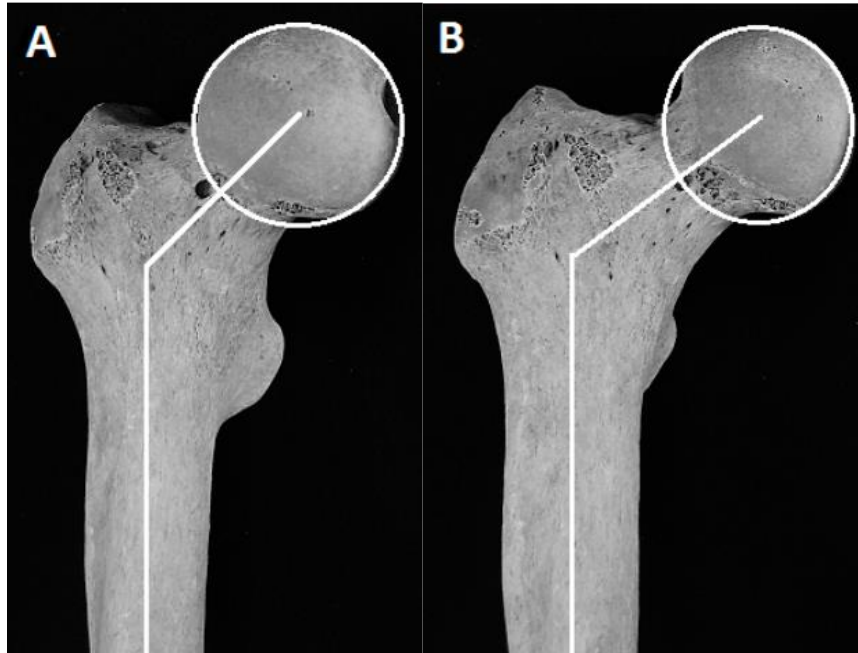


Figure 5-1: Radiographic (A) and anatomic (B) AP views of the femur used to measure the apparent and true NSA respectively. Figure A was obtained with the camera parallel to the femur, which is resting on the greater trochanter and the femoral condyles. Figure B is obtained by rotation the femur such that the femoral neck is horizontal and in a plane parallel to the camera, enabling us to measure the true NSA. Note the fovea is not visible and the lesser trochanter is less visible in Figure B, reflecting the rotation of the femur.

Figure 5-1a and 5-1b illustrate the two AP views, which we term the radiographic and anatomic AP respectively, used to measure the true and apparent neck-shaft angle.

Figure 5-1a illustrates the radiographical AP view, generated with the femur resting on the medial and lateral condyles distally and the greater trochanter proximally. The camera is placed parallel to the table, looking down at the femur. This represents the typical view seen on a supine AP radiograph, and was used to generate the apparent NSA. Figure 5-1b demonstrates the anatomical AP, generated by tilting the femur until the femoral neck is parallel to the table, judged by visual inspection. The distal end of

the femur was supported in this position with clay prior to photographing. This view was used to measure the true NSA, with the femoral neck and shaft in one plane perpendicular to the “beam”.

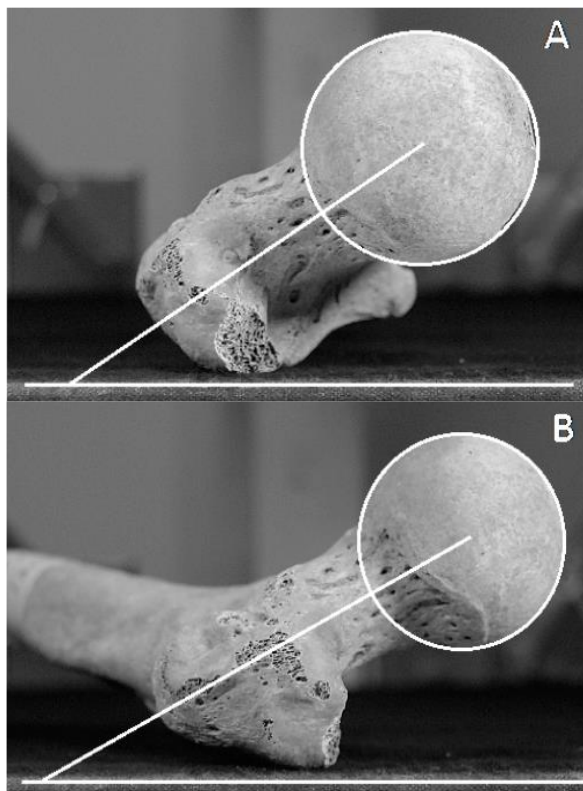


Figure 5-2: Axial photographs of the femurs used to measure the version and inclination angles, respectively. Figure A is obtained by placing the camera perpendicular to the femoral shaft, using the technique of Kingsley and Olmsted. Figure B is obtained with the camera in the same position, but with the femur rotated such that the femoral neck is parallel to the camera. Once again, this places the femoral neck in a single plane parallel to the camera, and allows for accurate measurement of the angle made with the table.

Similarly, figure 5-2a and 5-2b illustrate the two axial views, termed the version and inclination views respectively, along with the angles measured. Figure 5-2a was generated with the camera placed perpendicular to the table, such that the “beam” was directed down the femoral shaft. The femur, as in the radiographic AP, rested on its condyles and the greater trochanter. Figure 5-2b left the camera in the same position,

but rotated the femur to align the femoral neck perpendicular to the “beam” from the camera (parallel to the edge of the table). This enabled measurement of the angle made between the neck and the table in one plane, generating the inclination angle.

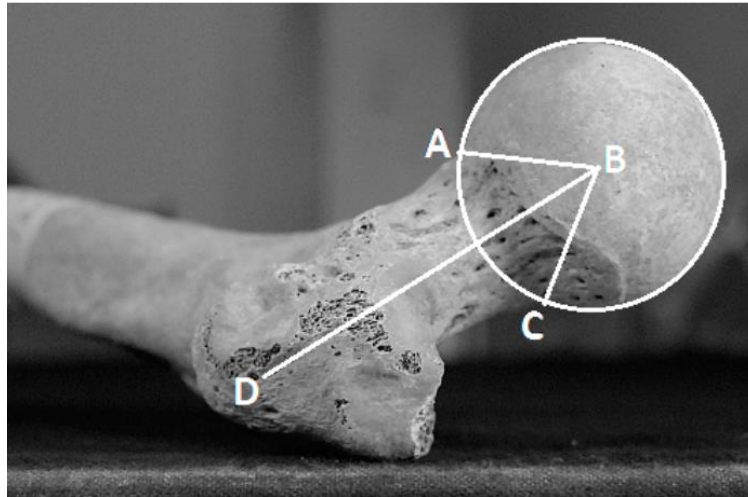


Figure 5-3: Inclusion view demonstrating the measurement of the alpha and beta angles. A circle is drawn encircling the femoral head and a line is drawn through the center of the femoral head through the middle of the femoral neck. Points A and C denote the points at which the femoral head “exits” the drawn circle on the anterior and posterior 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.

This inclination view was also used to measure the alpha and beta angle, as shown in figure 5-3. The alpha angle, first described by Notzli et al, is a measure of the sphericity of the femoral head. The original angle was described measured on tilted axial cuts on MRI parallel to the femoral neck, at the center of the femoral head. The inclination view we use mirrors the MRI cut described by Notzli, 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, the center of the femoral head, and the two previously marked

points were measured. The anterior angle constituted the alpha angle, while the posterior represented the beta angle.

Measurements were performed on ImageJ software (NIH, MA) on all femurs by one author (ARM, see acknowledgements). Additionally, a random sample of 20 femora were selected and measurements were repeated using custom designed software on MATLAB by another author (RB) to determine inter- and intra-observer correlation.

All statistical analysis was performed using SPSS 20.0 (IBM Corporation, MA), with a two-tailed p value less than 0.05 denoting significance. Inter- and intra-observer correlation was measured using the interclass correlation coefficient (ICC), with values greater than 0.65 denoting good correlation, and values greater than 0.75 denoting excellent correlation. Means, standard deviations, ranges were measured using commonly accepted formulae. Variables were correlated with age and sex of the population using the analysis of covariance (ANCOVA). Differences between sides were performed on the 74 specimens with bilateral femora using a pairwise student t-test.

Results

A total of 249 femurs (130 left, 119 right) were measured from 175 individuals (83 male, 63 female, 29 unknown). Table 5-2 shows the inter- and intra-observer ICC values, showing good or excellent correlation for all variables studied. Table 5-3 illustrates the means, standard deviations and ranges for all variables measured.

Table 5-2: Inter- and Intra-observer correlation for each variable studied

	Inter-observer correlation (ICC)	Intra-observer correlation (ICC)
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

Table 5-2: A sample of 20 femurs were selected and measured by two different researchers, using two digital methods. This table illustrates the inter- and intra-observer correlation coefficients for the variables measured to ensure accuracy.

Table 5-3: Means, standard deviations and ranges for the variables studied

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

Table 5-3: Means, standard deviations and ranges for each of the variables measured across all samples.

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 sided and right sided femurs. Table 5-4 demonstrates the variables found to have significant differences based on age or gender. Table 5-5 demonstrates the differences in measurements between left and right-sided femurs based on pairwise analysis of the 74 specimens with intact bilateral femurs.

Table 5-4: Effects of gender and age on variables studied using ANCOVA. Only significant results shown.

	Dependent variable/covariate	Left		Right	
		Predicted effect	p-value	Predicted effect	p-value
Version	Age	-0.187	0.038	N.S	
	Sex (Female)	N.S		N.S	
Inclination	Age	N.S		N.S	
	Sex (Female)	N.S		2.805	0.042
Alpha	Age	N.S		N.S	
	Sex (Female)	N.S		-2.333	0.01
Beta	Age	N.S		N.S	
	Sex (Female)	-2.608	0.002	-2.968	<0.001
Apparent NSA	Age	N.S		-0.179	0.035
	Sex (Female)	2.976	0.017	N.S.	
True NSA	Age	N.S		N.S	
	Sex (Female)	2.637	0.009	N.S.	

Table 5-4: The effect of gender and age on the variables were studied using analysis of covariance (ANCOVA), which allows the selection of multiple dependent variables. As this table shows, the effect of age and gender was inconsistent based on side studied, and only the beta angle was shown to be consistently affected by gender, across both sides.

Table 5-5: Effects of laterality on variables studied using pairwise student t-test

	Mean (left)	Mean (right)	p-value
Version	19.67	22.91	0.001
Inclination	18.23	20.49	0.006
Alpha	35.56	34.97	N.S
Beta	41.73	41.71	N.S
Apparent NSA	131.11	131.15	N.S
True NSA	123.32	121.84	0.001

Table 5-5: The effect of laterality on the measured variables, studied on paired femurs using a pairwise student t-test.

Discussion

We measured six angles using digital photographs on 249 femora from 175 individuals – the angles of version and inclination, the alpha and beta angle, and the true NSA and apparent NSA, using techniques described by Toogood et al.⁶³ We then examined if these measures varied within the population based on gender, age and laterality. The

effect of age and gender on the morphology of the proximal femur in our population is difficult to interpret. Most of the differences that were found to be significant were only found unilaterally (Table 5-4), and were modest in magnitude. Controlling for gender, version in left sided hips and apparent NSA in right sided hips were found to have a statistically significant, inverse relationship with increasing age. The beta angle was the only variable found to be different between genders in both left and right hips, with males having a slightly higher angle than females, and perhaps might point to post-developmental changes due to a lifetime of increased loading on the posterior hip.

Comparing our study to other modern day normal populations show some interesting differences. We compared our findings to results from the Hamann-Todd collection, a set of bones from modern humans, obtained in the early 20th century from unclaimed bodies at the Cleveland city morgue, using data from Toogood et al. Table 5-6 demonstrates the differences between measurements between the populations, along with the p-values for each.

	Mean (Libben)	Standard dev. (Libben)	Mean (H-T)	Standard dev. (H-T)	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	N.S
Apparent NSA	129.50	6.58	130.01	6.45	N.S
True NSA	121.96	5.10	129.23	6.34	<0.001

Table 5-6: The measured variables from the Libben collection (ancient humans) were compared to measurements on the Hamann-Todd collection (from modern humans) in order to identify the differences in morphology arising from modern behaviors. This table demonstrates modern femurs are less anteverted, and more varus, than ancient femurs. Importantly, the alpha angle is significantly higher in modern humans, implying that the cam deformity is a “new” injury pattern.

The Libben population hips were much more anteverted than modern humans, probably the result of squatting. Although the anatomical causation of increased anteversion by squatting is unknown, there is a correlation between the presence of increased femoral version, squatting facets on the distal tibia, platycnemia (a broadening and flattening of the tibia), and the knowledge that ancient populations were squatting.⁶⁴

The Libben population hips had much lower True NSAs than modern populations. A varus hip can be the result of increased loading prior to skeletal maturity⁶⁵, and it is conceivable that the prolonged walking and heavy lifting prior to adulthood as part of a hunter-gatherer lifestyle contributed to this adaptation. What is particularly interesting is that the apparent NSA is similar between populations. Liu et al demonstrated that the relationship between true and apparent NSA varies as a function of the cosine of the version angle.⁶⁶ 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.

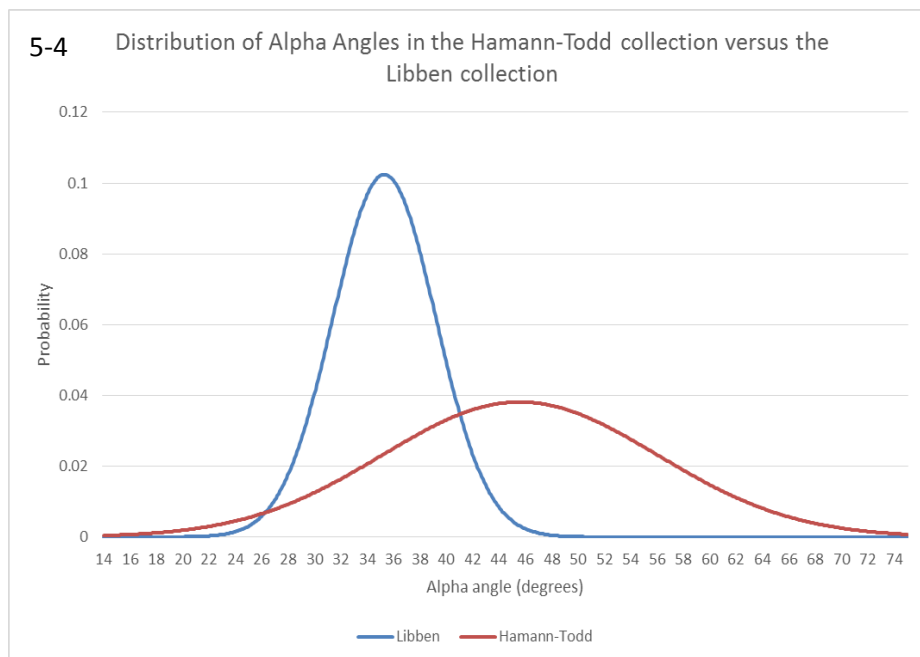


Figure 5-4: Normal curves demonstrating the distribution of alpha angles in the Libben collection and the Hamann-Todd collection. Note how the distribution of angles in the Libben collection (early humans) is much narrower, and does not include any hips demonstrating a cam deformity, defined as an alpha angle over 50 degrees. The Hamann-Todd collection (modern humans), on the other hand, shows a much wider spread, with almost a third of hips demonstrating an alpha angle over 50 degrees.

As hypothesized, the alpha angle is significantly different between the two populations, with the Hamann-Todd population showing a mean alpha angle almost 10 degrees higher than the Libben population. In fact, none of the 249 hips in the Libben population demonstrated an alpha angle over 50° – it seems the cam deformity was non-existent in these early humans. Figure 5-4 illustrates normal distribution curves for alpha angles in the two populations, illustrating a profound difference. Given our results, it appears that the cam deformity, defined as an alpha angle over 50°, is a product of modern living.

Reference	Population	Modality	Age range	Sample size	Average alpha angle (standard deviation)
Current study	Cadaveric specimens from 8 th -11 th C. humans (Ohio, USA)	Direct measurement	17-55	175	35.3 (3.9)
Toogood et al ⁶³	Cadaveric specimens of modern humans (Ohio, USA)	Direct measurement	18-89	200	45.6 (10.5)
Sutter et al ⁶⁷	Asymptomatic volunteers (Switzerland)	MRI	20-50	53	49.8 (7.2)
Kang et al ⁶⁸	Asymptomatic patients (New Zealand)	CT	15-40	50	45.6 (N.R)
Pollard et al ⁶⁹	Asymptomatic individuals (UK)	Crossleg lateral XR	22-69	83	48.0 (8.0)
Chakraverti et al ⁷⁰	Asymptomatic young patients(UK)	CT	20-40	50	46.0 (N.R)
Hack et al ⁷¹	Asymptomatic individuals (Canada)	MRI	21.4-50.6	200	40.8 (7.05)
Siebenrock et al ⁴⁷	Elite basketball players (Germany)	MRI	Physeal closure-25	16	50.9 (7.3)
Siebenrock et al ⁴⁷	Non-athletes (Switzerland)	MRI	Physeal closure-25	22	36.5 (5.5)
Malhotra et al ⁷²	Asymptomatic patients (India)	CT	40-80	85	45.6 (N.R)

Table 5-7: Comparing the Libben measurements to studies in other modern populations. Most populations mirror the Hamann-Todd collection in morphology. The only sample to be similar to the Libben numbers is from a group controlled for minimal athletic activity, in a study by Siebenrock.

Comparing results from our study to other modern human populations highlights a similar trend in distribution, as seen in Table 5-7.^{47,63, 67-72} Most modern populations studied have an average alpha angle similar to the Hamann-Todd sample. The exception is a population of 22 young non-athletes, specifically chosen to exclude individuals

performing more than 2 hours of physical exercise a week, reported by Siebenrock et al.⁴⁷ This seems to suggest that a potential explanation for the lack of a cam deformity in the Libben population could be a sedentary life style. However, it is unlikely that this 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 were almost certainly a reality for them. It is quite likely that healthy Libben adolescents punished their bones more like an elite athlete than the present day non-athlete Siebenrock used as a control group.

What, then, might explain the absence of cam in these ancient humans? One possibility is weight. It is likely the Libben population were significantly underweight, especially when compared to a modern population. While this could result in different femoral morphology in multifactorial means, one easily identifiable way could have been through subtle SCFEs, for example. It is well recognized that a significant proportion of cam deformities could be attributable to an unidentified slip prior to physeal closure, resulting in the formation of a “bump”, and an aspherical head.⁴⁸ In fact, this, and other childhood disease such as LCP, was long believed to explain all cases of FAI until Ganz suggested the existence of an idiopathic deformity. At the same time, childhood obesity is a well-documented risk factor in the development of SCFE. It is likely that a large factor explaining the difference between the morphology in the two populations is due to decreased childhood weight in the Libben population, and a subsequent decrease in childhood disease that might predispose an individual to a cam deformity.

Another important parameter in shaping the proximal femur of both modern and ancient populations might be diet. Being located in what was formerly the Great Black

Swamp, the environment had a wide variety of flora and fauna. Through analysis of pit remains, the population is believed to have used much of their surrounding vegetation and animal life as 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.⁷³ The pit remains also showed a heavy reliance on fish from local water sources, small game from the surrounding marshes, and mammals such as white-tailed deer and muskrat.⁵⁷ Recent analysis of dental remains indicates that maize was an important component of their diet, too.

The presence of fat and protein in present day abundance, was unlikely at Libben. It may be that physical activity in the presence of a modern diet is important in the development of this deformity, not simply activity alone. We speculate that intense activity and a modern diet provokes much cam; average activity and a modern diet (as seen in many contemporary groups) provokes some cam; minimal activity and a modern diet (Siebenrock's controls) provokes little cam; and a punishing lifestyle with an archaic diet (Libben) provokes none.

This study has several limitations. First, we only looked at one view in determining the alpha angle, in accordance with the original concept put forward by Notzli. While this provides a measure of the concavity of the femoral head in the anterior position, many studies have suggested that the maximal alpha angle is often at a more anterosuperior position.^{25, 28} Perhaps a more accurate estimate of the prevalence of the cam deformity in the Libben population could have been obtained by measuring the alpha angle in an oblique plane. However, this would have made it significantly more difficult to

standardize femoral positioning, and would have increased errors in measurement.

Additionally, this would have precluded direct comparison with the Hamann-Todd and other modern populations.

A more critical limitation is that our knowledge of behaviors in this 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 is notably absent in this population. Our comments regarding its development are offered in the spirit of academic speculation, which might lead to testable hypotheses.

Chapter 6 – Conclusion

Since Ganz et al introduced the concept of femoroacetabular impingement at the turn of the millennium, there has been a rapid expansion of the orthopedic literature expounding upon the clinical presentation and outcomes of this condition. This excitement among the orthopedic community is certainly warranted; the concept helps explain the etiology behind hip pain and the development of osteoarthritis that would have been otherwise considered idiopathic. As with Wiberg and his dysplastic hips almost a hundred years prior, this concept attributed the development of osteoarthritis to specific mechanical stresses as a consequence of abnormal morphology. These morphologies were elegantly divided into two categories – cam, involving a deformity on the femoral side, and pincer, involving a deformity on the acetabular side.²¹

The pincer deformity is perhaps the more complex of the two. While broadly referring to impingement resulting from an acetabular deformity, the pincer morphology includes a number of different subtypes. The mechanism of impingement is believed to be the repeated impaction of the femoral neck on an overarching acetabulum. Indeed, Ganz et al demonstrated that the pattern of labral damage noticed on dislocation of hips with acetabular protrusio was consistent with this hypothesis.²² However, perhaps due to the relative complexity of the pincer deformity, or the relatively recent elucidation of the mechanism, there are no studies that conclusively demonstrate the contribution of an overcovered hip to the development of arthritis. Similar to a dysplastic hip, it would seem that there would be a threshold CE angle at which a hip is likely to develop early onset degeneration. Bardakos et al studied radiographic measures determining the

progression of arthritis in a subset of hips followed over at least 10 years, finding that an increased CE angle was not associated with the progression of osteoarthritis.⁴⁰ Gosvig et al, in a cross-sectional study, looked at overcovered hips with a CE angle greater than 45° and found that overcoverage significantly increased the risk ratio for the development of joint space narrowing.⁴¹ However, one of the drawbacks of using similar cross-sectional methodology in analyzing the effect of overcoverage is that the development of osteoarthritis and joint space narrowing results in an alteration of the CE angle, resulting in difficult to interpret results.

Therefore, we set out to answer the question: *What is the role of an overcovered hip in the development of osteoarthritis? Is there a threshold CE angle that can be identified to define a pincer deformity on the basis of the clinical probability of secondary osteoarthritis?*

We planned on doing this by comparing radiographs of hips with no evidence of osteoarthritis between patients under 35 years of age and patients over 65 years of age. Comparing the prevalence of overcovered hips across these two populations would enable us to determine if these hips were underrepresented in the older population, allowing us to speculate that this was because of a “drop-out” of these hips due to the development of early arthritis. As expected, dysplastic hips were underrepresented in the older population. Presumably, these hips develop arthritis and are excluded from the older, healthy hips. Interestingly, we did not see a similar exclusion among overcovered hips. In fact, these hips were overrepresented in the older population. We believe that unlike dysplasia, overcoverage does not, in itself, predispose hips to early

arthritis. Likely, a combination of overcoverage, intrinsic chondral properties and lifestyle factors is required for the development of arthritis in these individuals.

Unlike generalized overcoverage, the role of retroversion to the development of arthritis has been explored.^{38, 43} The mechanism by which a retroverted hip is predisposed to arthritis, however, is not completely understood. It is generally thought that retroversion causes focal anterior overcoverage, which then impinges upon the femoral neck, leading to labral damage and arthritis. This is different from other mechanisms of pincer impingement, which generally stem from a globally overcovered hip. It would seem that the proposed mechanism would require a certain amount of acetabular cover to cause impingement and it is unclear if the effect of retroversion would persist in the absence of adequate coverage.

This led us to question: *Does retroversion cause osteoarthritis in undercovered hips? Or would the mechanism of localized anterior overcoverage secondary to retroversion only predispose individuals to arthritis in the presence of a normally covered hip?*

Again, we compared groups of healthy hips below the age of 35 years and above the age of 65 years to catalog the subset of hips that “make it” to 65 without arthritis. CE angle was measured in all hips, and hips were graded for the presence of signs of retroversion by blinded observers. These hips were grouped into two sets based on CE angle, with an angle of 30° or less defining an undercovered hip, and an angle greater than 30° defining a normally covered hip. The proportions of retroverted hips between the older and younger populations were compared for each of these groups. We found that, for the

normally covered group, retroverted hips were underrepresented in the older population, as expected. This seems to suggest that retroversion results in the development of early arthritis, and these hips “drop out” of our older sample. However, when we looked at the undercovered group, the prevalence of retroversion was consistent among the two populations. It seems that a similar “drop out” does not occur in the presence of undercoverage. We believe that undercoverage is, in a sense, protective against the effects of retroversion, since there is inadequate acetabular cover for the retroversion to result in impingement. Although our results are convincing, further study is required to more completely understand and identify the precise effects of overcoverage and retroversion on the development of early osteoarthritis.

The cam impingement is perhaps better understood and studied compared to the pincer deformity. Arising principally from the impaction of an aspherical head into acetabular cartilage, the cam deformity has been known for decades for its appearance as a “pistol-grip” on plain films, predating Ganz and his colleagues, although it was they who first described the mechanism of impingement leading to pain and arthritis.¹⁶ Aside from the natural history of this deformity and its treatment options, the source of this deformity has been extensively studied as well. Prevailing hypothesis, championed by Siebenrock and colleagues, describe the role of subtle physeal injury and growth plate migration prior to closure, resulting in asymmetric growth of the femoral head.⁴⁷⁻⁴⁸ Pollard et al elegantly described a genetic influence using twin studies, indicating that the deformity may arise long before any damage to the physis due to athletic activity.⁵¹ Evolutionary

studies attribute the appearance of the deformity to the rise of obligate bipedalism in humans, citing a need for increased stability at the expense of hip range of motion.⁵⁴

We sought to answer the question: *What is the antiquity of the cam deformity? Did it arise from an evolutionary shift from facultative bipedalism to obligatory bipedalism, from a need for increased stability at the cost of range of motion? Or is it a more modern injury, arising as a consequence of current day activity and behavior?*

We studied femora from 8th-11th century humans from the Libben osteological collection, measuring characteristics such as the alpha angle, neck-shaft angle and version. We compared these quantities to measurements on modern humans from the Hamann-Todd collection, finding that modern humans have a significantly larger neck shaft angle with a less anteverted hip. Importantly, it appears that there was no cam deformity, judged by the alpha angle, in the ancient humans. It would seem that the cam deformity is a product of modern stresses, be it diet or behavior. The relative contributions of each is difficult to ascertain. However, we speculate that both are necessary for the development of the deformity. Increased athletic activity with a modern diet high in fat and protein provokes large cam deformity, while a sedentary lifestyle with a modern diet has a smaller effect. Our study seems to suggest that a punishing lifestyle, with restricted caloric intake, provokes none.

We set out to expand on the current orthopedic literature studying femoroacetabular impingement. As this disease is understood further, we start to unravel the precise etiology and effect of these deformities on patients. Understanding this will allow

orthopedic surgeons to tailor treatments to patients with these morphologies, perhaps focusing on prophylactic surgery or preventive behaviors. The current literature, although vast, is still well short of this point. Although we have addressed some gaps in the etiology of the cam deformity, and the role of retroversion and overcoverage in the development of osteoarthritis, changes to clinical practice hinge on the results of longitudinal research. However, our work provides some guidelines that can be used to further our understanding of this disease, as we await the results from these long term studies.

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