CRANFIELD UNIVERSITY

Emma Louise Saunders

Femoroacetabular Impingement and Cam Morphology: Contributions to Bioarchaeology and Forensic Anthropology

Cranfield Defence and Security
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PhD
Academic Year: 2016 - 2020

Supervisor: Dr Nicholas Marquez-Grant
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Abstract

Femoroacetabular impingement is a clinical disorder of the hip caused by premature contact between the femur and the acetabulum. A lead cause of this condition is cam morphology, additional bone growth on the anterior aspect of the femoral head. Cam morphology has been associated with physical activity due to its high prevalence rates in athletes compared to non-athletes. A link between non-metric traits of the femur, particularly; Poirier's facets, plaque and cribra, and cam morphology has been suggested due to their shared location and suggested aetiology. Osteitis pubis, an overuse syndrome of the pubic symphysis, is believed to be a compensatory injury of femoroacetabular impingement.

The overall aim of this study was to determine the contributions of femoroacetabular impingement to the disciplines of bioarchaeology and forensic anthropology, with regards to femoral non-metric traits analysis, activity reconstruction and awareness of conditions that may affect the formation of biological profiles. To achieve this, this study aimed to establish if there is a link between cam morphology and non-metric traits of the anterior aspect of the femur. This would provide further understanding of the respective/joint aetiologies through the use of multidisciplinary literature. It also aimed to determine if the development of cam morphology is linked to occupational physical activity. Additionally, this study looked to determine if any osseous changes are present in individuals with femoroacetabular impingement in association with cam morphology, to allow the identification of symptomatic individuals when the presence of clinical information is not available. Finally, it also aimed to determine if there is a link between cam morphology and osteitis pubis at the pubic symphysis. This would contribute to both bioarchaeology and forensic anthropology, by highlighting a condition which may impact an area commonly used for the age estimation.

Two skeletal collections, the Wharram Percy collection and the Luís Lopes Identified Skeletal Collection, and a clinical comparison sample were utilised. These collections were selected due to presence of contextual information regarding lifestyle and occupation in different forms. The clinical comparison sample consisted of 3D volume rendered CT models of individuals being investigated for femoroacetabular impingement and a control sample. Non-metric traits of the femur and commonly used clinical measures to determine the presence of cam morphology were recorded on all samples. Recording criteria for osteitis pubis was developed and applied to the pubic symphysis of the two skeletal collections. Comparisons of these measurements were made within and between the samples.

The results of this study have shown there is a link between Poirier’s facets and plaque with cam morphology. Through the use of contextual information, it is recommended this association is a functional adaptation. There was no association between cam morphology, alpha angle size and occupational physical activity groups in adults. It is suggested cam morphology is therefore a better indicator of activity levels, or other extrinsic factors, requiring additional stability at the hip during skeletal maturation. No clear osseous indicators of the presence of FAI due to cam morphology were identified. Therefore, it is not possible to identify symptomatic individuals through skeletal changes alone. There was also limited evidence of a link between osteitis pubis traits and alpha angle size. Although eburnation could be an indicator for the later stages of this condition, however, there is the requirement for further study to confirm this.

Keywords: Femoroacetabular impingement, cam morphology, physical activity, non-metric traits, osteitis pubis

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Chapter 1. Introduction

Bioarchaeology is the study of human remains from archaeological context (Knüsel, 2010) and it recognises the entwined connection between biology and culture. The context, in the form of living conditions, climate and diet (inferred or documented), is as much a vital component in understanding more about the populations understudy as the human remains themselves (Larsen, 2015a). While forensic anthropology is the "*application of anthropological method and theory to matters of legal concern, particularly those that relate to the recovery and analysis of the skeleton*" (Christensen et al., 2014), anthropology is an extremely broad field involving the study of humankind (its name is derived from the Greek *anthropos,* meaning man and *logia,* meaning study). Forensic anthropology falls within the biological/physical anthropology discipline, typically involving the formation of a biological profiles from skeletal remains. Forensic anthropologists are also involved in the search and recovery of human remains, trauma analysis, taphonomy interpretation and age estimation in the living (Christensen et al., 2014). This study aims to analyse femoroacetabular impingement within the context of both bioarchaeology and forensic anthropology, to determine the contributions, awareness and understanding of this condition can have towards these two disciplines.

Femoroacetabular impingement (FAI) is a motion-related clinical disorder of the hip caused by premature contact between the femur and the acetabulum, leading to hip pain and activity limitation (Griffin et al., 2016). For establishing a diagnosis; symptoms, imaging findings and clinical signs must be present (Griffin et al., 2016). The most common symptoms include groin or hip pain, restricted hip flexion and internal rotation (Clohisy et al., 2009) which are typically motion or position related (Griffin et al., 2016). The two causes of FAI are cam and pincer morphology; however, this research will primarily be focused on the former. Cam morphology of the proximal femur is abnormal additional bone growth causing the femoral head to lose its typical spherical shape, whilst pincer morphology is anterior over coverage of the acetabulum. The most commonly used radiographic measures to determine cam morphology include alpha angles (Nötzli et al., 2002) and, to a lesser extent, femoral head-neck offset (Eijer et al., 2001), while for pincer, cross-over sign (Jamali et al., 2007) and centre-edge angle are used (Tannast et al., 2007). The two causes of FAI typically present in differing patient demographics, with young active males more frequently presenting with cam morphology, while pincer morphology is more commonly seen in middle-age women (Ganz et al., 2003). Cam morphology has been associated with physical activity due to higher alpha angle sizes and prevalence rates in athletes compared to non-athletes as reported by various authors (e.g. Frank et al., 2015; Lahner et al., 2014b; Ayeni et al., 2014; Siebenrock et al., 2011; Agricola et al., 2012). Groin pain is one of the most common symptoms of FAI with restricted hip flexion and internal rotation (Clohisy et al., 2009; Philippon et al., 2007; Larson et al., 2013; Weir et al., 2011).

Osteitis pubis is an overuse syndrome at the pubic symphysis causing pain and tenderness at this area. It is believed to be one of the most chronic and incapacitating conditions to affect athletes (Rodriguez et al., 2001). Several authors have proposed osteitis pubis is a compensatory injury of FAI due to the limited range of motion at the hip (e.g. Voos et al., 2010; Verrall et al., 2007; Verrall et al., 2005; Hammoud et al., 2014; Larson et al., 2013). It has been suggested that the alteration in motion due to the impingement at the hip leads to changes in muscle forces across the pelvis, particularly excessive strain across the joints and a compensatory increase motion at other areas of the pelvis (Voos et al., 2010). Further to this, Matsuda et al. (2015) recommended initial surgery for FAI with subsequent osteitis pubis only if symptoms persist in patients co-afflicted with both conditions.

Non-metric traits are variations of the normal skeletal anatomy (Saunders and Rainey, 2007). They have traditionally been used to determine biological affinity within and between skeletal populations (Stirland, 1996) however, with a primary focus on cranial traits, there were fewer studies dedicated to infracranial traits (Donlon, 2000). Due to their location, non-metric traits of the femur have been commonly associated with physical and habitual activities (Odgers, 1931; Angel, 1964; Kostick, 1963; Charles, 1893) however their true cause is still unclear. Villotte and Knüsel (2009) suggested a possible association between non-metric traits of the anterior aspect of the femur, particularly, Poirier's facets, plaque and cribra (or Allen's fossa) and cam morphology, due to the shared location and suggested aetiology. This study therefore aims to determine if there is a link between non-metric traits of the anterior aspect of the femur and cam morphology, as although these suggestions have previously been made in the literature (e.g. Villotte and Knüsel, 2009; Radi et al., 2013; and Mellado and Radi, 2015), few bioarchaeological studies have combined commonly used measurements for determining the presence of cam morphology with methods of scoring non-metric traits. There is currently a wealth of studies regarding FAI and non-metric traits of the femur separately within the clinical and anatomical/bioarchaeological literature respectively. By determining if there is an association between any of these non-metric traits and cam morphology this will allow a multidisciplinary approach to be taken to understanding more about their respective and/or joint aetiologies. This would enable these traits, commonly recorded but rarely used in bioarchaeological interpretations of past populations, to be reassessed and potentially contribute to the further understanding of the lifestyle of these archaeological populations. In addition to this, by using skeletal collections with a large amount of contextual information available, a bioarchaeological approach can be taken to determine more about the cause of cam morphology and these non-metric traits. The ability to identify FAI on bone has forensic applications as an additional identifying feature when an ante-mortem record of this condition is present. Increasing awareness of methods to record this condition bone is vital but also determining a link between these non-metric traits and FAI, which are easily recorded through visual observation, would reduce time and resource requirements needed to carry out measurements currently used to record the presence of this condition.

The study of osseous changes caused by habitual patterns of activity is an important, although controversial, aspect of bioarchaeological analysis and, to a lesser extent, forensic investigation. It is contentious for various reasons including; lack of clear definitions of activity in many studies, assumptions of a simple cause and effect relationship between activity and the observed skeletal markers, as well as, failure to recognise potential multifactorial aetiologies (Jurmain and Cardoso, 2011). The most commonly used methods include entheseal changes, osteoarthritis (or degenerative joint disease) and long-bone diaphyseal cross-sectional geometry (CSG) (Nikita et al., 2019). Additional stress lesions and activity-related dental wear have also been used (Meyer et al., 2011). The fundamental idea that forms the basis of these methods is termed “bone functional adaptation”, the idea that the bone alters per the stresses applied to it to reduce the risk of damage from repeated habitual activity (Meyer et al., 2011). There is however a tendency to assume simple cause-and-effect relationship between occupation and skeletal changes when many changes are multifactorial in aetiology (Jurmain and Cardoso, 2011). Lawrence et al. (2018) used cam morphology as an indicator of habitual activity and therefore socioeconomic status for an archaeological population. Although cam morphology is associated with athletic activity, currently no previous study has tested to determine if this is the same for occupational physical activity. In addition to this, authors have suggested cam morphology is present in equal amounts in both physical activity and non-physically activity individuals. Athletes are more likely to become symptomatic due to the more extreme and frequent movements at the joint and are therefore more commonly diagnosed with FAI (Johnson et al., 2012). Using analysis of an identified skeletal collection, with occupational information, and a rural population, with a large amount of skeletal and historical evidence of activity, this study aims to determine if occupational activity is associated with increased alpha angle size and cam morphology. This would have bioarchaeological applications as it will confirm or deter the use of cam morphology as a marker of occupational activity in the study of past populations. Measurements of cam morphology are easy to perform, non-destructive and do not require a large amount of equipment, therefore it's use as an additional marker of activity would be extremely advantageous.

The diagnosis of FAI requires a triad of symptoms, clinical signs and radiological findings to be present (Griffin et al., 2016). It is not however possible to determine two out of three of these findings in skeletal remains without a medical history, which is rarely available. Therefore, the ability to determine if there are any osseous changes which are more common in symptomatic individuals would be useful bioarchaeologically for palaeopathological investigation. Due to the activity limiting nature of advanced FAI, the ability to identify symptomatic individuals would be useful in palaeopathological analysis in populations or groups where subsistence strategies rely on the ability to be physically active. This also has applications to forensic anthropology in victim identification, again with regards to an additional identifying feature, although this cannot be relied on alone, it may assist in cases with an ante-mortem record of this condition. This study therefore aims to determine if there are any osseous changes that are observable in symptomatic individuals that are not present in the asymptomatic.

Age estimation is a fundamental aspect of both bioarchaeology and forensic anthropology. In archaeological populations, it is an essential aspect in determining palaeodemography, while in forensic anthropology it is a major part of the reconstruction of a biological profile (Mays, 2015). The pubic symphysis is one of the most commonly used areas for age estimation from the skeleton (Todd, 1921; Brooks, 1955; McKern and Stewart, 1957; Katz and Suchey, 1986; Brooks and Suchey, 1990). This is due to the successive changes which occur and the fact these changes continue in adult life, which is commonly difficult to identify in the rest of the skeleton (McKern and Stewart, 1957). An aspect to all methods of ageing from osteological material is that bone is an active tissue which is subject to renewal, repair and remodelling in response to different stresses (Cox, 2000). Bone adapts, within certain limits, to changes and demands placed on it, responding to trauma, weight bearing and disease (Cox, 2000). Mays (2015) provided a review of factors other than age that can affect frequently used adult bony age markers including; sex hormones, pathology, biomechanical forces and genetic factors. They suggest approximately 60% of variation in skeletal age indicators is due to factors other than age (Mays, 2015). One such factor included in their review was osteitis pubis. Osteitis pubis has not been widely studied in the bioarchaeological literature, limited to possible case reports by Judd (2010), Gregg and Bass (1996) and Pfeiffer (2011). There are therefore currently no set recording criteria for this condition to allow its recognition on bone. To fully understand the appearance of FAI on bone but also to raise awareness of this condition which impacts such a widely used area, it was felt analysis of osteitis pubis was essential. It is important to understand any condition which can potentially affect areas used for age estimation and therefore the accuracy of these methods for both bioarchaeological and forensic analysis. Inaccurate age estimations could be particularly detrimental to a forensic investigation by excluding the correct individual or including the wrong identified. While in bioarchaeological study this could impact interpretations of demographic data. This study therefore aims to form recording criteria for observing this condition on bone via the clinical literature's description of osteitis pubis on medical imaging. This will then be used to determine if there is an association between the appearance of osteitis pubis criteria at the pubic symphysis and alpha angle size at the femur.

In summary, the study of FAI and cam morphology could provide contributions to disciplines of bioarchaeological and forensic anthropology in many ways including; further understanding of non-metric traits of the anterior aspect of the femur, habitual activity determination, factors influencing accurate age-at-death estimates and victim identification. This study intends to achieve its aims through the use of two skeletal collections and a retrospective comparative clinical sample. The skeletal collections are; the Luís Lopes (or Lisbon) identified skeletal collection and the Wharram Percy collection. The Luís Lopes collection is an identified skeletal collection and therefore known information regarding, age, occupation and sex is available for each individual. While the Wharram Percy collection is a well-documented and studied archaeological collection. The two collections represent two very different contexts, with the Luís Lopes collection representing a late 19th-early 20th century urban populations, while the Wharram Percy collection is a (predominantly) medieval rural population. These collections were selected due to this very different social context, with diverse levels of activity. Additionally, the Luís Lopes collections also has recorded occupation information for many individuals, which is use in this study for determining the impact of occupational activity on the presence of cam morphology, as discussed previously. The comparative clinical sample is made up of 3D volume rendered hip CT scans from individuals being investigated for FAI (FAI group) and a random sample of individuals being investigated for reasons other than FAI (non-FAI group). The FAI group was included to act as a clinical comparison to provide the opportunity to observe and analyse osseous changes on examples known to have the condition understudy. This modern sample was included in this study as FAI has not widely been considered within skeletal collections. It was therefore felt it was important to include examples where the individual was being investigated for this condition clinically due to the presence of symptoms. This also provides an opportunity to fully understand the impact of this condition on bone without relying solely on descriptions in the clinical literature which typically focus on the area of interest of that particular study. The non-FAI sample was included to allow comparisons of osseous traits to be made between those with symptoms, and therefore being investigated for FAI, and those not being investigated for this condition. This was to determine if there are traits which are indicative of FAI and therefore can be used to indicate symptomatic individuals based on osseous changes alone. The expectation was those in the FAI group would have a higher prevalence of cam morphology and non-metric traits as well as higher alpha angles than the non-FAI group.

1.1. Aims

The main research aims for this study therefore include:

1) To determine if there is a link between non-metric traits of the anterior aspect of the femur and cam morphology, via alpha angle measurements
2) To explore if there is a link between the prevalence of cam morphology and occupation activity
3) To determine if there are any observable osseous differences between those with symptomatic cam morphology and asymptomatic controls
4) To determine if there is a link between cam morphology and osteitis pubis at the pubic symphysis

1.2. Thesis outline

This thesis is organised into nine chapters, including the current introduction chapter. Chapter 2 will focus on the anatomy and morphology of the hip joint to provide an understanding of the normal anatomy and therefore how changes to this area could affect a number of functions. A discussion of non-metric traits including a brief history of these skeletal variations. A focus will be provided on non-metric traits of the anterior aspect of the femur to provide an understanding of the current uncertainties surrounding these traits.

Chapter 3 is an overview of FAI and cam morphology. A discussion on the current methods used to determine the presence of cam morphology will be given and how this can be transferred to use on skeletal remains. Additionally, the current theories on the suggested aetiologies and rates recorded in different populations will also be reviewed. It will also give an overview of the association between cam morphology and osteitis pubis and how this has been studied from a bioarchaeological standpoint with future implications.

Chapter 4 is focused on the materials and methods used for this study. The first section will address the samples collected, why they are relevant for use in this study and ethics. For both skeletal collections there is a brief section on contextual information to provide a biocultural perspective to the findings for later use in the discussion. The second section is focused on providing an outline on the methods used, why they have been selected and an outline on the statistical tests used.

The results chapters have been broken down by sample starting with chapter 5 presenting the results for the clinical CT sample, chapter 6 the Wharram Percy collection, Chapter 7 the Luís Lopes collection, Chapter 8 is focused on results from combining and comparing the data between each sample.

The discussion of the results from this research can be found in chapter 9. This chapter is broken down into each research question to ensure each question is addressed. Additionally, any limitations to the study and future work can also be found in the chapter along with the overall conclusions for this study.

Chapter 2. The Hip Joint: Anatomy, Morphology & Non-metric Traits

This chapter will focus on the anatomy and morphology of the hip joint, with a focus on the femur. Initially an overview of the anatomy and development of the hip will be given to provide context to the area under study and a reference to the areas which are being discussed throughout this thesis. Following this, the morphology of the human hip has been focused on, including its evolution and anatomical variation. This section has been included to address the various factors which can impact this area of the skeleton, and the changes which can occur to the 'normal' form due to these factors. The final section will address non-metric traits, giving a brief history followed by a discussion on the current issues within the literature regarding the recording, naming, and understanding of the cause of these traits at the anterior aspect of the femur.

2.1. Anatomy of the hip joint

The hip joint is a diarthrodial ball and socket joint surrounded by a synovial capsule (Cheatham and Hanney, 2016). The femur articulates with the acetabulum, see Figure 2-1, (of the os coxae) and distally with the tibia and patella.

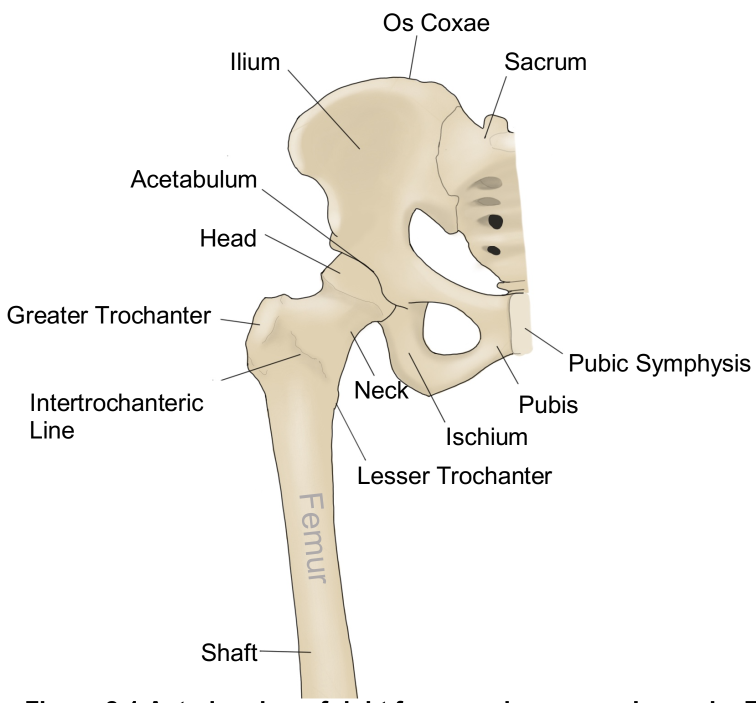


Figure 2-1 Anterior view of right femur and os coxae. Image by E. Saunders

The acetabulum

The acetabulum is orientated laterally and tilted slightly anteriorly and inferiorly (Cheatham and Hanney, 2016). Figure 2-2 shows a section through the hip joint. The acetabulum, with the labrum, covers 50% of the femoral head. The lunate surface is a horse shoe-shaped area of hyaline cartilage covering a portion of the acetabulum and articulates with the femoral head. At the inferior portion of the acetabulum is the acetabular notch which contains the transverse acetabular ligament. The centre of the acetabulum is called the acetabular fossa, this area is deeper than the articular surface (Tönnis, 1987). The acetabular labrum is composed of fibrocartilage and attaches from the acetabular rim over the femoral head (Tönnis, 1987). Inferiorly, the labrum fuses with the transverse acetabular ligament closing the acetabular fossa (Cheatham and Hanney, 2016). The labrum aids in joint stability, shock absorption and load distribution. A negative pressure develops within the joint when traction is exerted on the femur which helps to keep the two articular surfaces together (Tönnis, 1987). The hip capsule attaches to the acetabular rim medially and extends over the labrum. Anteriorly the fibrous capsule extends to the base of the femoral neck and inserts on the intertrochanteric line (Tönnis, 1987).

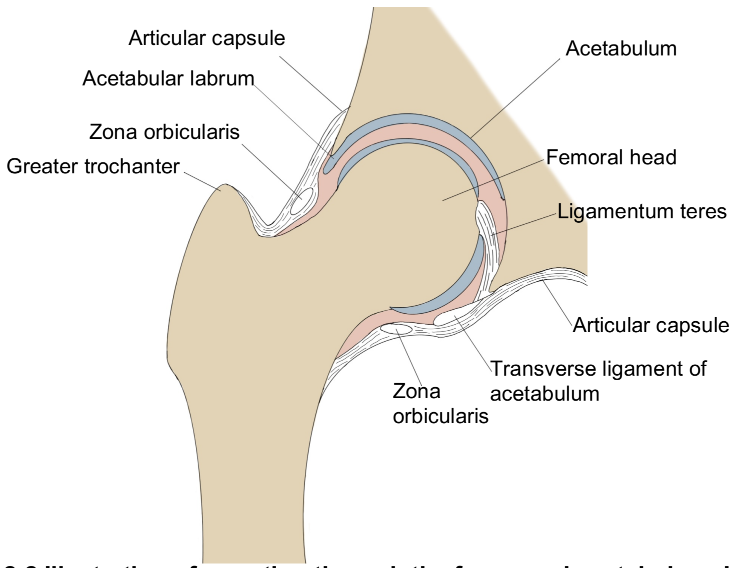


Figure 2-2 Illustration of a section through the femur and acetabulum. Image by E. Saunders

The proximal femur

The proximal femur consists of the femoral head, neck, greater and lesser trochanters (see Figure 2-1). The femoral head is a round structure covered in a layer of hyaline cartilage. At the centre of the femoral head is a pit called the fovea capitis. The ligamentum teres connects the femoral head, via the fovea capitis, to the acetabulum (Scheuer and Black, 2000). A minimal blood supply is provided to the head by the foveal artery through the ligamentum teres into the fovea capitis (Konda, 2018). The femoral head contains the epiphysis and growth plate. The greater trochanter projects superolaterally to the gluteus medius, gluteus minimus, piriformis and obturator internus muscles attach. The obturator externus muscle attaches to the intertrochanteric fossa which is found on the posteromedial aspect of the greater trochanter (Scheuer and Black, 2000). The lesser trochanter is inferior to the femoral head and greater trochanter, and is the attachment site of the iliopsoas muscle. The intertrochanteric line is present between the two trochanters anteriorly and the iliofemoral ligament attaches here, while on the posterior aspect the intertrochanteric crest is the attachment of the quadratus femoris muscle (Scheuer and Black, 2000). The muscles of the hip are shown in Figure 2-3.

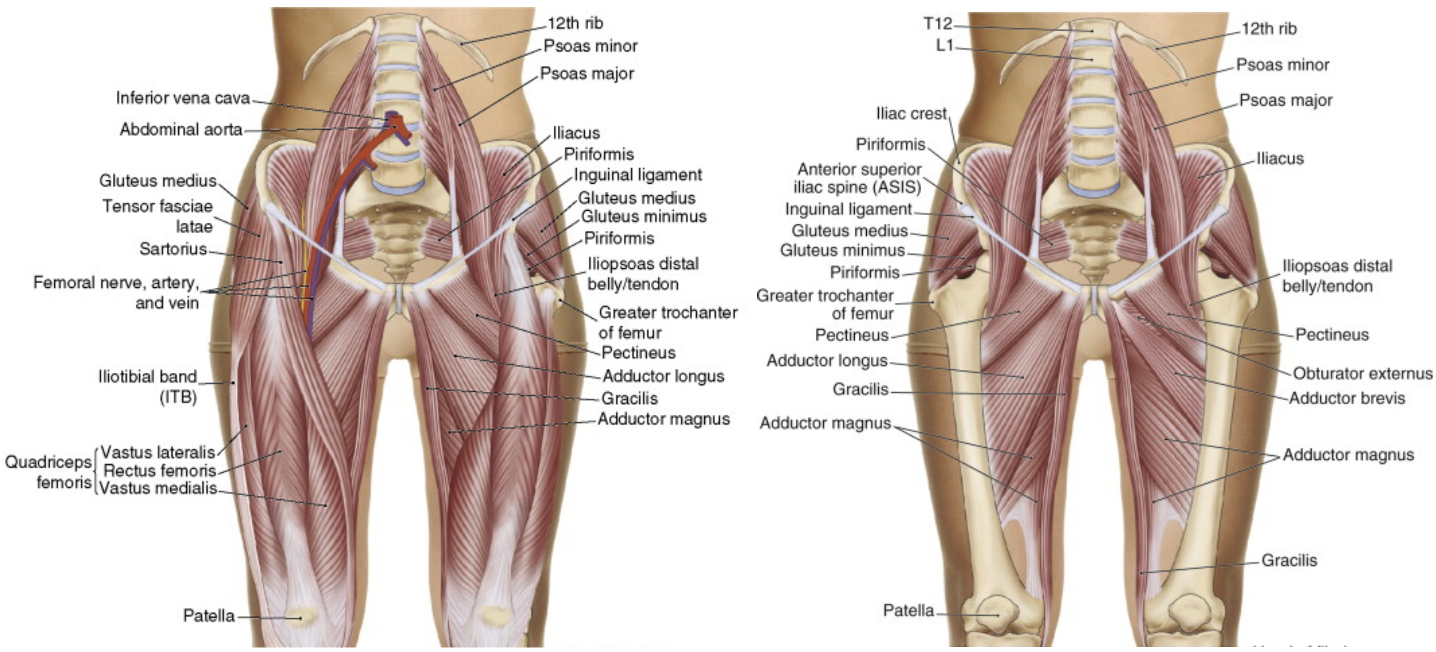


Figure 2-3 muscle of the hip and thigh, illustration from Simancek (2013)

Ligaments and blood supply

The main ligaments of the hip joint are; iliofemoral, ischiofemoral, pubofemoral, ligamentum teres and the transverse acetabular ligament, see Figure 2-4 (Cheatham and Hanney, 2016). The ischiofemoral ligament is involved in internal rotation of the hip, the lateral aspect of the iliofemoral ligament controls internal rotation in extension and external rotation in flexion and extension, while external rotation in extension is controlled by the pubofemoral ligament (Konda, 2018). The blood supply to the femur is provided by the medial and lateral circumflex femoral artery, retinacular arteries and the acetabular branch of the obturator artery. Many muscles work together to enable the complex movement at the hip joint (Cheatham and Hanney, 2016).

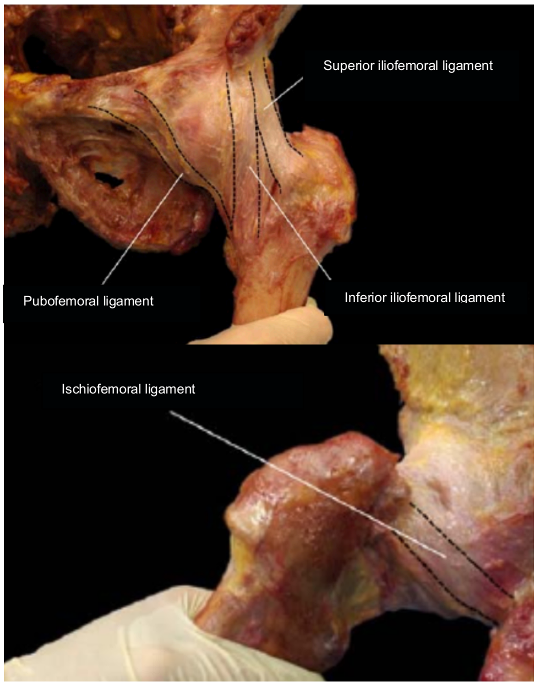


Figure 2-4 Ligaments of the hip, Image from Hidaka et al. (2015)

Ossification and fusion of the femur

At birth the femoral shaft is largely ossified however the proximal femur is still cartilage with one growth plate (Malviya et al., 2014). The extension of the femoral neck allows separation into two separate areas for the femoral head and greater trochanter, as shown in Figure 2-5 (Scheuer and Black, 2000). By one year the secondary ossification centre for the femoral head appears and then around 2-5 years the secondary ossification centre for the greater trochanter is developed (Schaefer et al., 2009). The proximal femur has three main growth areas; the proximal femur epiphyseal plate, the greater trochanter growth plate and the femoral neck isthmus (a growth plate between the two around the lateral border of the femoral neck) (Malviya et al., 2014). The shape of the femoral neck depends on the balanced growth of these three areas (Malviya et al., 2014). The growth of the proximal femur is also influenced by the action of the muscles, weight bearing, joint nutrition, circulation and muscle tone. A change in any of these factors can cause changes in development (Weinstein and Dolan, 2018).

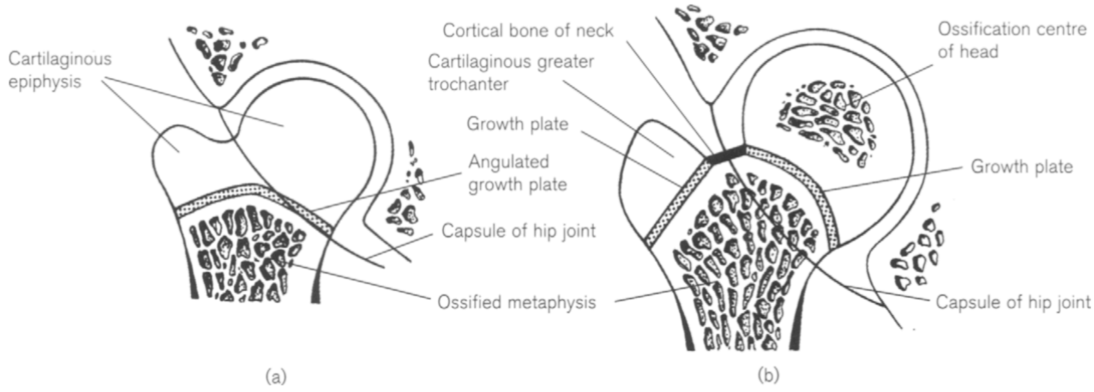


Figure 2-5 The development of the proximal end of the femur. (a) At birth (b) 3-4 years, image from Scheuer and Black (2000)

In early adolescence, epiphyseal fusion of the proximal femur occurs. The timings of epiphyseal fusion has been found to be sex and population specific (Sullivan et al., 2017; Cardoso, 2008) and can be impacted by socioeconomic conditions and nutrition (Cardoso, 2008; Schmeling et al., 2006). During skeletal maturation, the femur fuses at several locations at approximately different times of development, as shown in Figure 2-6, however this can vary between individuals (Scheuer and Black, 2000). Dry bone specimens and radiographic analysis have been used to determine the age of epiphyseal fusion and this has therefore been used in age estimation methods. Scheuer and Black (2000) reported the femoral head to fuse at 14-19 years in males and 12-16 years in females, the greater trochanter to fuse at 16-18 years in males and 14-16 in females, while the lesser trochanter fuses at 16-17 years in both males and females. Various studies have aimed to determine the age of epiphyseal fusion finding different rates in in various populations and therefore the requirement to use methods relevant to the individual/population under study (McKern and Stewart, 1957; Schaefer, 2008; Coqueugniot and Weaver, 2007; Cardoso, 2008; Sullivan et al., 2017). Many of these methods are not however without their problems including; the use of samples with older lower age limits (e.g. 17 years for McKern and Stewart,1957), the use of males only (McKern and Stewart, 1957; Schaefer, 2008;) glued or damaged epiphysis (Coqueugniot and Weaver, 2007), low numbers per age range categories (Cardoso, 2008).

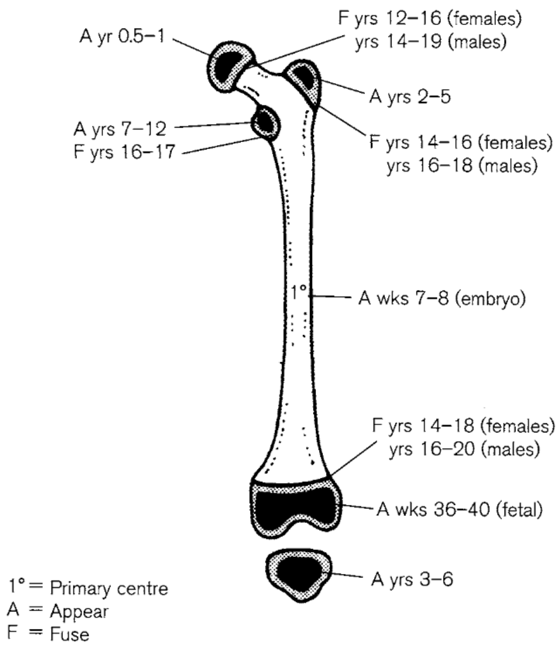


Figure 2-6 Appearance and fusion of femoral ossification centres, image from Scheuer and Black (2000)

Currently there is no literature with regards to the effect of physical activity on epiphyseal fusion time. This is likely due to the wealth of factors which may have an impact on the recorded rates. Through a review of the literature Mirtz et al. (2011) suggested high levels of physical activity during skeletal immaturity can lead to widening of the epiphyseal growth plate due to extension of hypertrophic chondrocytes into the metaphysis due to disruption of the blood flow, as reported by Laor et al. (2006) for the knee. It is however unclear how this would affect fusion timings.

2.2. Hip morphology

The human hip has been found to be pliable area of the skeleton which varies from birth to maturity. The hip has adapted and developed dramatically over time to become the form seen today. Variation in hip morphology continues to occur (to a much lesser extent) and various factors have been found to impact the 'normal' morphology of this area (although some are debated in the literature). This section outlines how the human hip has evolved over time and some of the main factors believed to influence these adaptations. Factors that continue to cause variation in human hip morphology will also be addressed. This section has been included to fully understand the various factors which can impact this area of the human skeleton and show how adaptable it is. This is to understand what is currently known about variation to hip morphology prior looking into hip variation in relation to cam morphology.

Evolution of the human hip

Human hip morphology has evolved to allow energetically efficient bipedal habitual mobility and encephalization (Gruss and Schmitt, 2015), this is illustrated in Figure 2-7 which presents how the pelvic morphology has evolved from chimpanzee to man. The shape of the pelvis has evolved considerably from the long, narrow and flat pelvis seen in apes to one which is shorter, wider and more curved (Hogervorst et al., 2009). The dramatically shorter ilium in humans, when compared to chimpanzees, provides a lower centre of mass, closer to the hip joints, and therefore reducing the effort for the muscles to hold this posture (Lovejoy, 1988). The ischium is long and the ischial tuberosity faces downwards in apes, while in humans the ischium is shortened and the ischial tuberosity is angled upwards, allowing the origin of the hamstrings to be further away from the insertion (Gruss and Schmitt, 2015).

Figure 2-7 Image from Hogervorst et al. (2011) demonstrating the evolution of the pelvic morphology from chimpanzee to man

While the upper half of the pelvis is largely adapted for bipedal gait, the changes in the lower half of the pelvis are to enable the birth of a foetal cranium which was increasing in size. In apes the true pelvis is larger in anterior-posterior (A-P) than Medial-Lateral (M-L) dimensions (Hogervorst et al., 2009), while humans have a narrower birth canal in the A-P dimensions and wider M-L dimensions, due to the wider sacrum (Gruss and Schmitt, 2015). With increase in brain size the pelvic opening had to become wider, the flare of the ilium was reduced and the head of the femur became larger to withstand the increased pressure of the abductors (Lovejoy, 1988). The M-L widening of the pelvic midplane and outlet in humans causes the hips to be further apart, which in turn increases the work required by the abductors. To retain an energy efficient bipedal gait the femoral neck was lengthened. There is however a limit to this and therefore other adaptations occurred, such as enlargement in the A-P direction via lengthening of the pubic rami and deepening of the acetabulum (Hogervorst et al., 2009). “Lucy” (AL288-1), the *Australopithecus afarensis* female fossil, is the most used case for early bipedal mobility (Lovejoy, 1988). The pelvis of Lucy shows the hallmarks of bipedal gait but with some dissimilarities from the human pelvis due to the increase in brain size of the last 3 million years (Lovejoy, 1988). Lucy’s pelvis is thought to be better adapted for bipedal gait than the human pelvis with more flared ilia and longer femoral necks (Lovejoy, 1988). In ‘Lucy’ there is A-P narrowing of the pelvic inlet and midplane due to widening of the sacrum, therefore causing widening in the M-L direction (Hogervorst et al., 2009). This was acceptable for Lucy as the cranium of her infant was smaller than in modern humans (Lovejoy, 1988). The changes in the human pelvis and the influence on hip morphology is a combination of the requirements for child birth and bipedal gait. Hogervorst et al. (2011) suggests the variation in proximal femur morphology, in relation to cam morphology, is due to several of these evolutionary adaptations. They suggest differences in hip morphology between males and females are due to adaptations to different requirements. The same requirements for childbirth in females are not required in males. Hogervorst et al. (2011) suggests, loading history is more of an influencing factor in males due to the requirement for a sturdier hip. Additionally, Rudolf (1922) and Kappelman (1988) have suggested adaptations of the proximal femur morphology dependent on habitual environment in certain species.

Factors impacting ‘normal’ hip morphology

Human hip morphology varies throughout development and growth but also due to additional factors, such as; disease or habitual activity. There are several measures commonly used to describe hip morphology including; angle of torsion and neck-shaft angle. Many of these parameters change from birth to skeletal maturation and through degeneration.

The angle of torsion (or femoral version) is formed between the femoral head and neck, which can either be anteverted or retroverted, as seen in Figure 2-8. Anteversion occurs when the femoral head-neck junction is more anteriorly orientated in relation to the transcondylar axis, while retroversion is a more posterior orientation (Cheatham and Hanney, 2016). The femoral neck is ante-verted at approximately 35° at birth, which reduces in the first 10 years of life towards approximately 15° (Malviya et al., 2014). The degree of femoral version can impact the range of motion of the femur and is a risk factor for labral tears (Cheatham and Hanney, 2016).

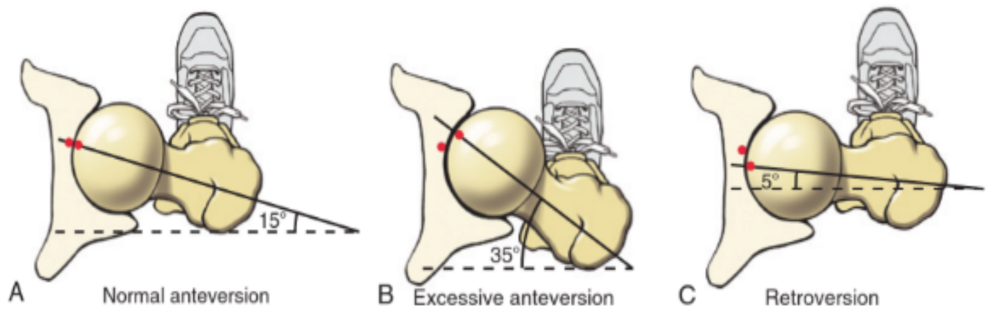


Figure 2-8 Femoral angle of torsion from Neumann (2010)

Various factors have been reported to impact the angle of femoral version including; genetic predisposition (Upadhyay et al., 1990), sex (Wescott et al., 2014; Jiang et al., 2015), habitual activity/sitting or sleep postures (Moats et al., 2015; Cibulka, 2004) and obesity (Galbraith et al., 1987). In their study of femoral version in children aged 3-5 years, Upadhyay et al. (1990) found no significant difference in femoral anteversion between girls and boys or social class. They did however find a significantly negative correlation between femoral anteversion and age, as age increased femoral anteversion angle decreased. They also showed a potential genetic influence, as there was a high correlation of anteversion between siblings. This result could also be interpreted in a biomechanical sense. The environmental conditions for siblings are typically very similar and therefore they are likely to be subject to the same/very similar levels of activity. Biomechanical forces are believed to be the primary cause of changes in the angle of anteversion during skeletal maturation. Muscle growth and development, as well as tension from the joint capsule are believed to influence femoral torsion (Wescott et al., 2014). Any muscle imbalance during development, including over-activity of the iliopsoas and medial rotators, causes increased loading on the anterior aspect of the growth place leading to greater torsion (Wescott et al., 2014). With regards to habitual activity, when comparing the results of their study of femoral morphology of the Libben population[1] to that of the Hamann-Todd collection[2], Moats et al. (2015) found the ancient humans to have more anteverted hips in comparison to the modern humans. They attribute this to possible habitual squatting however this could also be attributed to differing levels of physical activity between the two populations.

During normal childhood development, the neck-shaft axis or the angle of inclination (see Figure 2-9) changes from an angle of up to 145° to the normal adult range of 120°-130°. The 'normal' change in femoral neck-shaft angle is believed to be in response to weight-bearing and the development of the hip abductors for walking (Scheuer and Black, 2000). Prior to walking the proximal epiphyseal surface is flat. The change in positioning of the thigh and hip when the child starts walking subjects the medial epiphyseal surface to greater stresses, which leads to growth (Child and Cowgill, 2017). The neck-shaft angle increases during this time compared to prior to walking. The decline in neck-shaft angle towards, that which is recorded in adults, is due to a shift in shear stresses across the epiphysis to a lateral position due to the activity of the abductors and change in gait pattern with maturation (Child and Cowgill, 2017).

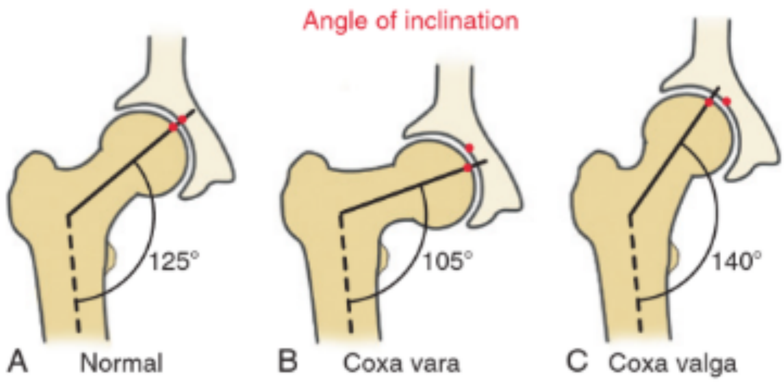


Figure 2-9 Femoral angle of inclination from Neumann (2010)

[1] The Libben site is situated in Ottawa County, Ohio on the banks of the Portage River with radiocarbon dating placed the site between A.D. 800 and 1100. 1327 individuals were excavated from the site (Lovejoy et al., 1977).

[2] The Hamann-Todd Human Osteological Collection is an early 20th century US skeletal collection, house at Cleveland Museum of Natural History, Cleveland, OH, USA (Mensforth and Latimer, 1989).

Coxa vara is a deformity of the proximal femur where there is a decrease in the neck-shaft axis angle away from the normal threshold. There are many causes of coxa vara however the most common is slipped capital femoral epiphysis (Shapiro, 2019). While coxa valga is a pathological increase in the neck-shaft angle away from the 'normal' range (Cheatham and Hanney, 2016). Population-based variability in neck-shaft angle has been reported in the literature however it is debated whether this is truly regional differences or if this reflects climate adaptations (Gilligan et al., 2013; Weaver, 2003) or differences in habitual activity (Anderson and Trinkaus, 1998; Weaver, 2003; Child and Cowgill, 2017). Gilligan et al. (2013) analysed if habitual activity and regional differences in body size due to climatic adaption is likely to have an impact on neck-shaft angle. They found higher neck-shaft angles in warmer regions and lower angles in colder regions. While there was only a slight trend towards an increase in neck-shaft angle from foragers to agricultural and urban populations, therefore indicative of only a minor influence of habitual activity. While Anderson and Trinkaus (1998) suggested habitual activity played more of a role in neck shaft angle, finding an increase in mean neck-shaft angle with increasingly sedentary lifestyle and mechanisation. Determining the level of physical activity from general subsistence levels does however have its limitations, particularly when it has been suggested the changes in neck-shaft angle occur during skeletal maturation and habitual activity typically represents occupations in adults. Child and Cowgill (2017) measured both neck-shaft and relative body mass in geographically diverse sample of immature holocene remains to determine if the neck-shaft angle is due to "ecogeographic body proportions". In their study they suggest the decline in neck-shaft angle seen during development is similar in those with similar gait and behaviours, and the differences in body proportions between populations does not impact this. The differences in regional body proportions were seen to be strongly influenced by ecogeographic principles. They therefore suggest other factors are likely to impact the differences seen in neck-shaft angle (Child and Cowgill, 2017).

Another factor considered to impact neck-shaft angle is sexual dimorphism. There are discrepancies in the literature with regards to sexual dimorphism and neck-shaft angle with some authors reporting differences between males and females (Igbigbi, 2003; Pujol et al., 2016; Gómez Alonso et al., 2000; Boese et al., 2016; Nissen et al., 2005) while others do not (Gilligan et al., 2013; Anderson and Trinkaus, 1998). When a difference is found, adult females are typically reported to have a lower angle than males. The widening of the pelvis in females is believed to be a contributing factor to the decrease in the neck-shaft angle, however as Pujol et al. (2016) observed larger variability in boys compared to girls they hypothesised the differences between the sexes could also be due to levels of physical activity (Pujol et al., 2016). Hormonal differences could also be an impacting factor. Pujol et al. (2016) found limited differences in male and female neck-shaft angles until the onset of puberty. From the age of 10 years there was a significant difference between the sexes reaching average difference of 10° at 14 years. Nissen et al. (2005) cited a significant difference in neck-shaft angle between pre- and post-menopausal women but not with age. The angle was lower in the post-menopausal women at 128° vs 130° for pre-menopausal women. The lack of a correlation between age and neck-shaft angle in men or women in this study suggests there is another impacting factor causing this difference, potentially hormonal differences.

A study by Toogood et al. (2009) was the first of its kind to provide values for defining the adult proximal femur and the relationship between the femoral head and neck in a normal ('healthy') population. In this study, existing quantitative measurements of the proximal femur was combined with novel measurements of femoral head rotation using digital photography of femora from the Hamann-Todd skeletal collection. For the whole sample the femoral head was translated anterior and inferiorly, rotated via abduction and anteversion, and had greater concavity inferiorly and posteriorly (Toogood et al., 2009). They also showed sexual dimorphism in several measurements; male femora were more inferiorly translated, had more abduction and anteversion than female femora. This study/ explored correlations between numerous morphological factors to be investigated, which had previously not been done before. Measures of concavity correlated with measures of translation; the more anteriorly the femoral head was positioned, the more it was concaved anteriorly and less concaved posteriorly. In addition to this, the more superiorly positioned the femoral head, the more concaved superiorly and less concaved inferiorly it was (Toogood et al., 2009). Although valuable insights into proximal femur morphology have been determined from this research, the nature of the samples caused some limitations. Little is known on the health, nutrition and lifestyle of the individuals within the sample therefore it is not possible to determine the influential factors leading to these differences. The measurements were also taken on bone specimens and therefore cannot be directly compared to the same measurements on medical imaging. More research is however using the method by Toogood and colleagues on medical imaging such as volume rendered CTs e.g. Zhang et al. (2015).

Summary

Through this review of the current literature it is clear a combination of multiple factors cause great variation to proximal femoral morphology, with habitual activity and loading being a consistent factor throughout. Further analysis of variation at this area could be of great value to the disciplines of bioarchaeology and forensic anthropology particularly with regards to activity reconstruction and identification. For many years' activity reconstruction has been attempted by bioarchaeologists using skeletal evidence. The most commonly used methods include; entheseal changes (e.g. Havelková et al., 2011; al-Oumaoui et al., 2004; Palmer et al., 2014; Takigawa, 2014; Schrader, 2015), osteoarthritis (or degenerative joint disease) (e.g. Larsen et al., 1995; Sofaer Derevenski, 2000; Larsen and Thomas, 1982; Eshed et al., 2010; Molnar et al., 2011) and cross sectional geometry (e.g. Shaw and Stock, 2009; Ruff et al., 1993; Holt, 2003; Shackelford, 2007; Ruff, Larsen and Hayes, 1984; Marchi et al., 2006). While, as described previously, femoral neck shaft angle and torsion (or version) have been used by many researchers to indicate a change in the level of activity over time, few studies have incorporated other measures such as alpha angles or offset ratio, as described in the study by Toogood et al. (2009). Knowing this area of the skeleton has been suggested to show great variability due to activity it is unclear why there are few studies analysing these additional measures when activity reconstruction is of such great interest in the field of bioarchaeology. Additionally, Toogood and colleagues have shown a level of interaction between the various measures of proximal femoral morphology therefore to gain complete understanding of these changes at this area, potentially due to habitual activity, analysis of these less studied measures is essential to this discipline.

2.3. Non-metric traits

Non-metric traits, also known as discontinuous morphological traits, epigenetic variants, or discrete traits, are minor variants from 'normal' human anatomy (Saunders and Rainey, 2007). They can be present in all human tissue and since they were first discovered hundreds of these traits have been recorded on the skeleton (Saunders and Rainey, 2007). Typically, they are classified as either hyperostotic, caused by excess bone formation, or hypostotic, caused by incomplete ossification or impeded development (Saunders and Rainey, 2007). Hundreds of non-metric traits have been identified however there is currently no standardised classification system for cranial and post cranial traits. Several authors have developed their own classification systems such as; Finnegan (1978) and Saunders (1989) however, this lack of standardisation limits the amount of comparison that can be made between studies.

Non-metric traits have a long and controversial history with regards to understanding their cause and classification. Originally described by the Dutch anatomist Kerkring in 1670, they gained a lot of interest in the 19th and 20th century sparked by the recognition that many of these traits could potentially have a genetic basis and therefore could be used to inform the interaction between genotype and the environment (Tyrrell, 2000). This formed the theory that these traits could provide information on biological relationships in past populations when similar frequencies of traits were observed (Saunders and Rainey, 2007). It was not until the 1950s when Grüneburg published their mouse studies that there was a better understanding of these traits and their genetic basis (Tyrrell, 2000). In their studies, including various elements e.g. third molar eruption, inherited variations of the vertebrae and pelvis, Grüneburg developed the idea of the quasi-continuous nature of these traits. This idea suggested the genetic interpretation previously used to describe their development was not as simple as first assumed. That there is an underlying continuous genetic basis to many traits but threshold factors (typically environmental or developmental) causes them to be expressed in a discontinuous manner (either present or absent) (Grüneberg, 1952). Later studies found that these conclusions may not have been accurate due to problems with the genetic lines of the mice used e.g. Howe and Parsons (1967). During this time populations studies used non-metric trait analysis to determine biological distance in human populations (Saunders and Rainey, 2007).

The Berry and Berry (1967) paper created a renewed interested in non-metric traits in archaeological study and there was an increase in biological distance and inter-group variation studies using these traits (Tyrrell, 2000). For their study, Berry and Berry (1967) analysed 585 adult crania from a variety of geographical locations and in some cases across different time periods. They boldly proposed that the differences in the expression of these traits in different populations suggests genetic differences and that as non-metric traits were not impacted by age, sex and side they were more useful than metric traits in determining genetic relationships (Berry and Berry, 1967).

A large portion of this work on the use of non-metric traits to determine biological distance has primarily focused on cranial rather than infracranial non-metrics. Donlon (2000) suggests this is potentially due to the decline in studies focused on biological distance at the time of increased interest in infracranial non-metrics. Studies by Finnegan (1978) and Saunders (1978) both suggested infracranial traits were as useful as cranial traits in this regard (Donlon, 2000).

Studies of biological distance using non-metric traits continue today (Weiss, 2018; Rathmann et al., 2017; Brasili et al., 1999; Nikita et al., 2012). With the advent of many new technologies, recent studies have looked further into this possible association between non-metrics and genetics, and are likely to continue to do so (e.g. Herrera et al., 2014; Hubbard et al., 2015). The true cause of non-metric traits is, however, still not clearly understood. The lack of understanding surrounding the impact of age, sex, asymmetry, activity, body size and genetics makes their usefulness in forming interpretations regarding past populations difficult. In addition to this few studies have previously reported inter- and intra-observer error rates leading to concerns regarding repeatability and comparability between studies (Tyrrell, 2000). There is also no standard recording system consistently used for their scoring making inter-study comparisons difficult.

2.3.1. Non-metric traits of the anterior aspect of the femur

Terminology

Non-metric traits of the anterior aspect of the femur have been observed and recorded for many years, originally pictured and described in anatomical atlases and texts in the 19th century (Radi et al., 2013). Since then there have been many reports of osseous traits at the anterior aspect of the femoral head-neck junction by researchers. These traits were difficult to distinguish from each other due to overlapping terminology and descriptions for the same observations under different names. This confusion was highlighted by Odgers (1931) when they analysed the presence of *the eminentia* *articularis colli femoris* and the *empreinte,* see Figure 2-10 below. The *eminentia articularis colli femoris* was named by Fick in 1904 but first described by Sudeck in 1899. Odgers (1931) described it as:

"A prominent compact bar stretching from the superior tubercle of the intertrochanteric line to the head of the bone"

While the *empreinte,* also known as the cervical fossa by Allen in 1882, and the Empreinte Illiaque by Poirier in 1911 (highlighting the number of terms being used to describe the same trait), was described by Odgers (1931) as:

"…a depressed irregular roughened area, in which the bone is eroded to a greater or lesser extent"

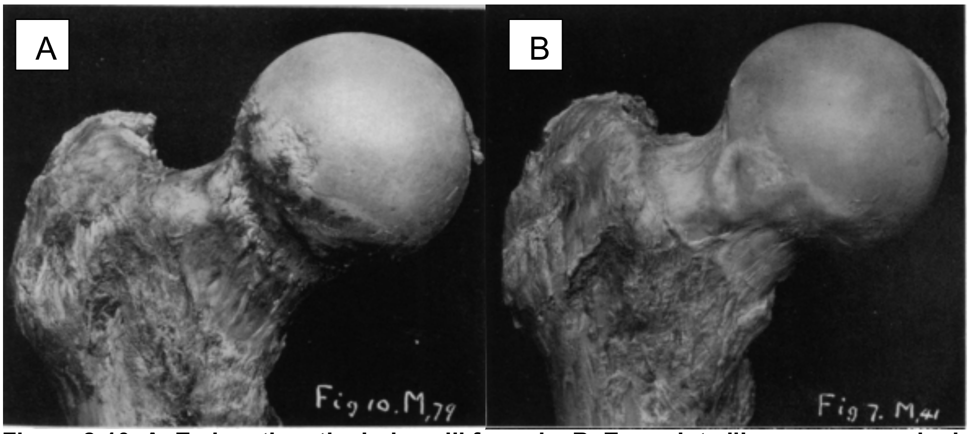


Figure 2-10. A. Eminentia articularis colli femoris, B. Empreinte iliaque- very marked erosion, Image from Odgers (1931)

Odgers found researchers at the time had been confusing the different terms when describing the same observable traits. The example presented is of Fick describing an elevated area of bone, but saying it is what Poirier referred to as Emprinte illiaque rather than eminentia articularis colli femoris. This confusion is also highlighted in an article by Angel (1964) where they refer to plaque as "*an overgrowth or bony scar from the ring of bone surrounding the fossa*" but suggesting this is the same as Poirier's empreinte iliaque or Fick's eminentia articularis, two very different traits. In addition to this Pearson and Bell (1919) include areas of bone erosion, likely to be Allen's fossa, in the categories of various types of Poirier's facets. Parsons (1914) combined the different types of traits into one category of "the pressure facet", which they describe as "the presence of a roughness or depression…may be covered with articular cartilage." A large amount of confusion seemed to have surrounded Allen's fossa as shown in table 2.1 below. The cervical fossa had been originally described by Allen in their 1882 anatomical atlas followed by Bertaux in 1891 (Meyer, 1924). Soon after, this trait was known by various names including the empreinte by Poirier in 1911 (Odgers, 1931), the anterior cervical imprint (Kostick, 1963) and the anterior acetabular imprint (Meyer, 1924). More recently cribra femoralis or femoral cribra has been commonly referred to as the new term for the cervical fossa of Allen (or Allen's fossa) (Smith-Guzmán, 2015; Radi et al., 2013). Figure 2-11 shows what was considered by Radi et al. (2013) as femoral cribra while Figure 2-12 shows Kostick (1963)'s cervical imprint.

Figure 2-11 Femoral cribra from Radi et al. (2013) article

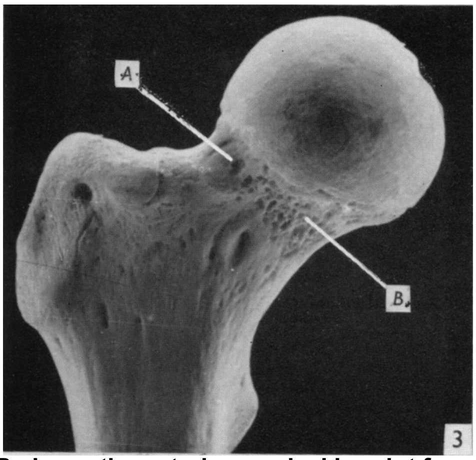


Figure 2-12 B shows the anterior cervical imprint from Kostick (1963)

From this confusion three main traits were repeatedly recognised, even if consensus regarding their names was not met. These traits included; a depressed or roughened area, typically known as Allen's fossa, cervical imprint or empreinte de Poirier; an extension of the articular surface of the femoral head towards to the femoral neck, Poirier's facets; and an extension from the femoral head towards the femoral neck but with a distinct edge and of a distinct form, typically known as plaque. Each of these terms have developed over time with changes in name and confusion continuing to exist in their descriptions. Angel (1964) attempted to provide clear distinction between Poirier's facets, Allen's fossa and plaque suggesting these traits occurred at a "sensitive reaction area" which is located at the anterior surface and medial end of a "bar of bone which runs medially from the upper anterior part of the greater trochanter over the head of the femur". Finnegan (1978) followed Angel in providing clear descriptions of each of these traits as there was still some confusion present in Angel's categories, Figure 2-13 shows the illustration of the non-metric traits from Finnegan's 1978 article to identify each trait. He described the traits as:

- Poirier's facet: *"…a noticeable…bulging of the articular surface of the femoral head toward the anterior portion of the femoral neck. The facet is necessarily smooth…"*
- Plaque: *"…overgrowth or bony scar can be defined extending from the area of Poirier's facet on the femoral head down on to the femoral neck where it often surrounds or covers Allen's fossa."*
- *Allen's fossa: "…located near the anterior superior margin of the femoral neck close to the border of the head…vary from a small depression to a large eroded area 1cm^2 where cortical bone has been lost exposing underlying trabeculae…"*

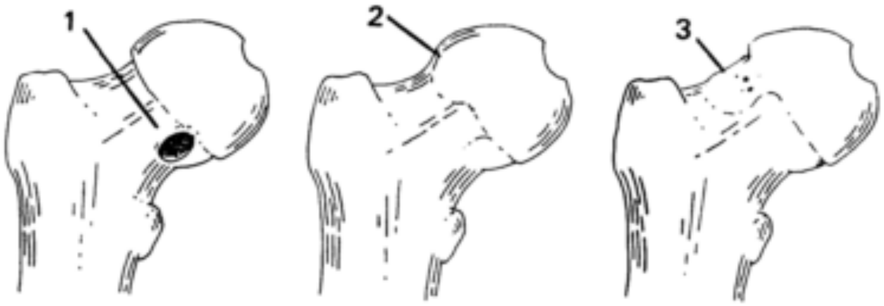


Figure 2-13 1. Allen's Fossa, 2. Poirier's facet, 3. Plaque, Image from Finnegan (1978)

Although Angel (1964) and Finnegan (1978) provided two systems for describing the presence of these non-metric traits Radi et al. (2016) attempted to create recording criteria to form a standardised method for recording these traits during detailed skeletal analysis. They extended the descriptions created by Finnegan to allow a clear less ambiguous scoring system. Figure 2-11, Figure 2-14 and Figure 2-15, show the images used in Radi et al. (2013)'s article to assist in defining cribra, plaque and

Poirier's facets to allow users to identify each trait when used in combination with their descriptions.

Figure 2-14 Examples of (A) plaque type A, (B) plaque type B, (C) plaque type C, from Radi et al. (2013)

Figure 2-15 Image showing a femur with Poirier's facets present from Radi et al. (2013)

Table 2-1. Descriptions and terminology for Allen's fossa from the literature

Author	*Allen’s fossa descriptions*	*Other terms*
Allen (1882) as cited by Meyer (1924)	“is marked in front near the articular surface by a faint depression, which is often cribriform in appearance and may receive the name cervical fossa”	-
Angel (1964)	“Varies from a mere depression to an area of removal of cortical bone a square cm in size, surrounded by slightly raised border and exposing cortical trabeculae whose edges appear to be thickened or raised”	Cervical fossa of Allen
Kostick (1963)	“Occurs on anterior and inferior aspect of medial part of the neck, adjacent to the head…Here divided into two types: Type A: • “ulcer-like excavation, exhibiting a floor and edges. Some cases have a clean punches-out appearance, with sharp edges and a depressed floor...The ridge divides the neck into a medial and a lateral portion, each with a bony surface of differing texture…” Type B: • “Discontinuity in the normal bony appearance of the neck…May show ‘moth-eaten’ or worn cancellous appearance, as though the cortical bone had been gradually erased…Situated on the antero-inferior aspect of the neck adjacent to the epiphyseal margin.”	Anterior cervical imprint, fossa of Allen, imprint of Berteaux
Finnegan (1978)	“Vary from a small depression to a large eroded area…where cortical bone has been lost exposing underlying trabeculae…Border of this fossa may have a ridge or thickening around it...”	Cervical fossa (depression of Allen)
Villotte and Knüsel (2009)	“Depressed and roughened area, in which the bone is eroded to a greater or lesser extent…”	Empreinte de Poirier, Cervical fossa, Fossa of Allen

Aetiology

The confusion surrounding the descriptions, classification and correct naming of these traits also enhanced the uncertainty surrounding their aetiology. The lack of standardised scoring systems meant it was unclear which traits were being recorded and their true prevalence. This confusion also made it difficult to surmise the true cause of each trait independently as it was ambiguous which trait was being referred to. Many authors have however attributed physical activity as the main aetiology due to their location on the proximal femur.

Hyperflexion has been proposed as a leading cause of these traits during certain activities, such as, horse riding (Molleson and Blondiaux, 1994), habitual squatting (Charles, 1893) and even sleeping on one side (Meyer, 1924). The mutual factor suggested between all these aetiologies is contact of the femoral head-neck junction against the acetabulum during full flexion (Parsons, 1914). The association of this to specific activities is typically based on the common activity performed in the population being observed. For instance, in their studies Andelinović et al. (2015) and Molleson and Blondiaux (1994) respectively, reported habitual osseous changes associated with horse riding. They both noted the presence of Poirier's facets, suggesting they were caused by abutment of the femur against the acetabular and Allen's fossa was caused by hyperflexion of the femur. During riding, the position required for sitting in the saddle causes the femur to be positioned in a way that could lead to the development of both traits. Charles (1893) believed that the hyperflexion and abduction of the femur, which occurs during habitual squatting, would cause the acetabular to come into contact with the anterior aspect of the femoral head and therefore a potential cause of these traits. Trinkaus (1975) and Kostick (1963) however argued that the presence of Poirier's facets and Allen's fossa in populations without habitual squatting suggests this is unlikely to be the direct cause. In addition to this Trinkaus (1975) commented that while in the squatting position the body weight is primarily placed on the anterior-inferior surface of the femoral head as opposed to the anterior superior portion where most of these changes occur, as shown in Figure 2-16. Instead they suggest it is likely Poirier's facets are caused by the amount of flexion and abduction during normal gait and the pressure from the iliopsoas or the rectus femoris tendon.

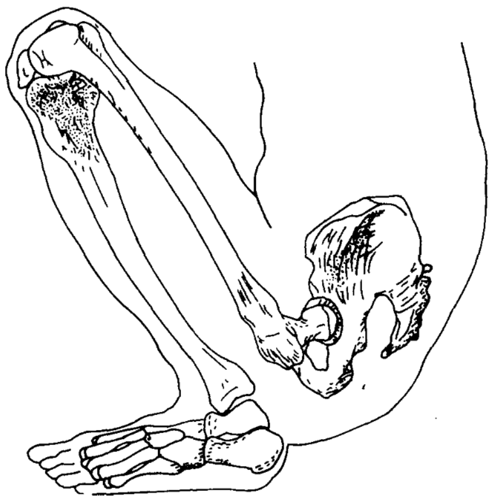


Figure 2-16 Image from Trinkaus (1975) demonstrating the position of the femoral head during squatting

Through observations from dissection, Odgers (1931) believed the level of flexion required for these traits to occur is not a natural position for people to adopt. Alternatively, full extension is more likely to cause these traits to develop (Odgers, 1931; Kostick,1963; Angel, 1964). Odgers (1931) proposed the eminentia acts as a "pulley bar" for the pressure from the joint capsule when the femur is in full extension and that males are more likely to develop this trait as the female gait requires less extension. They also proposed the zona orbicularis, circular fibres of the articular capsule around the neck of the femur, are well marked anteriorly and during full extension pressure and friction occurs. Fibro-cartilage extension is initial protection against this friction however when this breaks down it causes the empreinte (or Allen's fossa) (Odgers, 1931). Angel (1964) agreed with the theory that full extension of the hip is the likely cause of Allen's fossa though they attribute it to running or walking down hill as the actions leading to the tightening of the iliofemoral ligament. Angel (1964) hypothesised Poirier's facets to be caused by pressure and friction from the iliopsoas muscle and that both Allen's fossa and Poirier's facets are caused by more vigorous muscle functions, as they more commonly observed in males. As opposed to Odgers suggestion that cartilage extension was a protection method against the development of an Allen's fossa, Angel theorised plaque is an osseous healing reaction to the presence of a fossa (Angel, 1964). It still has not been determined what the cause of these non-metric traits of the anterior aspect of the femur is.

There has been considerably less work devoted on this area as there was in the past. This may be due to the uncertainty towards these traits or the view they are just variants of normal anatomy. The more recent literature regarding Allen's fossa uses the term 'cribra femoralis' and has advocated its use as a stress indicator (Wasterlain et al., 2018) but also related to certain diseases such as anaemia and malaria or part of intense growth periods (Djuric et al., 2008; Williams et al., 2004). It has typically been associated with those of younger age and due to its location by the femoral epiphysis some authors have suggested it is likely to arise during development, e.g. Smith-Guzmán (2015) and Kostick (1963). Djurić et al. (2008) observed cribra femoralis on the femora of individuals as young as 0-2 years and therefore, in this population, it is unlikely to be due to skeletal maturation. Both Djurić et al. (2008) and Wasterlain et al. (2018) reported high levels of cribra femoralis. In their study of a late medieval rural population in northern Serbia, Djurić et al. (2008) analysed the distribution of cribrous syndrome (defined as the association between cribra orbitalia, symmetrical femora cribra and symmetrical humeral cribra) on 107 subadults (< 14 years). They observed femoral cribra on 83.25% of femora and 33.33% of individuals had all three forms of cribrous lesions present. The authors attribute this high prevalence of cribrous syndrome to frequent infections, particularly parasitic leading to blood loss, diarrhoea, or anaemia. Wasterlain et al. (2018) analysed 31 non-adults excavated in Valle da Gafaria (Lagos, Portugal), in which, they reported a high frequency of cribra femoralis (85.7% of individuals). Evidence suggested that it is likely these individuals were African slaves and their estimated ages ranged from <1 to >15 with the largest number at 7-9 years. These individuals were thus likely to have lived difficult lives shown by the discrepancies between osteometric and dental data, as well as the high frequencies of enamel hypoplasia and other non-specific stress indicators. The authors suggest the observed cribra femoralis could be due to many factors likely to arise in these unfavourable conditions.

Cribra femoralis has also recently been suggested to be indicative of malaria when seen in combination with cribra orbitalia and porotic hyperostosis due to anaemia being a primary health impact of malaria (Smith-Guzmán, 2015; Wasterlain et al., 2018). Previous studies have found skeletal indicators of anaemia to be present in individuals testing positive for P. falciparum malaria via immunoenzymatic assay (Rabino Massa, 2000) and via aDNA (Nerlich et al., 2008). Walker et al. (2009) argued that megaloblastic (caused by vitamin B_{12} deficiency and haemolytic anaemia seen in individuals with malaria) could cause of porotic hyperostosis and cribra orbitalia instead of iron-deficiency anaemia, which was the long-standing belief. This article was debated in the literature with Oxenham and Cavill (2011) dismissing Walker's rejection of iron-deficiency anaemia's role in porotic hyperostosis and cribra orbitalia (Smith-Guzmán, 2015). Haemolytic anaemia is however one of the main health impacts of malaria due to destruction red blood cells. It is thought the impact on the skeleton is through acid phosphatase, free haeme and haemozoin in the blood which causes an imbalance in the remodelling and induction of extramedullary erythropoiesis which leads to cortical thinning (Smith-Guzmán, 2015). Few studies comment on cribra femoralis when studying skeletal manifestations of malaria, with cribra orbitalia and porotic hyperostosis being the most commonly recorded lesions (e.g. Gowland and Western, 2012). In their study into the skeletal lesions of malaria Smith-Guzmán (2015) found individuals with a cause of death of anemia or malaria had humeral and femoral cribra present, Figure 2-17 is from this study showing examples of femoral cribra. The frequency difference for these lesions was not however significantly different from those who died of other causes (however they lived in the same region so it cannot be ruled out they did not suffer from malaria or anaemia). They also found femoral cribra and humeral cribra were associated significantly but neither were associated with cribra orbitalia. This study suggests femoral cribra should be used as one of five skeletal lesions indicative of malaria. It is theorised that femoral cribra develops in younger individuals with anaemia during epiphyseal fusion. At this time there is an increase in erythropoiesis (red blood cell production) which causes expansion of the medullary cavity (Smith-Guzmán, 2015).

Figure 2-17 cribra femoralis as an indicator of malaria from Smith-Guzmán (2015)

Non-metric traits and cam morphology

Another recent development in determining the aetiology of these traits was made by Villotte and Knüsel (2009). In this article, they suggested an association between non-metric traits of the anterior aspect of the femur and cam morphology. Cam morphology is additional bone growth at the anterior-aspect of the head-neck junction. It is a lead cause of femoroacetabular impingement and has a suggested aetiology related to high levels of physical activity (more detail on cam morphology will be provided in Chapter 3). The similarity in location, potential cause and composition indicate a possible association between this disorder and these non-metric traits of the femur. Several articles have followed on from the initial hypothesis by Villotte and Knüsel (2009), for instance; Radi et al. (2013), Hogervorst et al. (2011) and Lawrence et al. (2018). There are few experimental studies which incorporate both measures of non-metric traits and those used clinically to determine the presence of cam morphology to test this hypothesis. One such study by Lawrence et al. (2018) concluded Poirier's facets and plaque may be caused by a similar process as femoroacetabular impingement. They showed significantly higher alpha angles in femora with Poirier's facets and those with type A and B plaque compared to those without plaque. Cribra was not included in this study there it is not clear if this trait is linked with FAI also. The current study therefore aims to determine more about these non-metric traits of the anterior aspect of the femur (including Poirier's facets, plaque and cribra) in relation to cam morphology on further skeletal collections.

Further investigation of the possible association between cam morphology and these non-metric traits has implications for both bioarchaeology and forensic anthropology. From a bioarchaeological perspective, there is a wealth of literature regarding FAI and cam morphology in the medical and sports literature and therefore a possible link would allow the utilisation of this literature to provide a better understanding of these traits, as well as an element of clarity with regards to their aetiology which is currently lacking. Additionally, due to the believed link between cam morphology and physical activity, this association could indicate the usefulness of these traits as a marker of activity. The forensic contributions are with regards to victim identification. The primary role of a forensic anthropologist during the identification process is to provide information from skeletal remains that could narrow the pool of potential identities through the comparison of post mortem to ante mortem data (Christensen et al., 2014).

The forensic anthropologist's analysis provides information on the biological profile of the individual including; age, sex and stature. In addition to this, other features on the skeleton are also assessed including; trauma, pathology and anomalies. The ability to identify FAI on bone would therefore be useful in the identification process where an ante-mortem record of this condition is present. Furthermore, with the methods to record non-metric traits being predominantly via qualitative observations on bone, while FAI/cam morphology determination typically being via quantitative methods which require equipment and software, an association between the two areas would allow identification of this condition on bone through gross inspection. This would therefore decrease the amount of time and resources required to identify this condition on bone.

Chapter 3. Cam Morphology & Femoroacetabular Impingement

This chapter will discuss the current concepts surrounding cam morphology and femoracetabular impingement. Particular focus will be on how it is currently defined, including debate with regards to measurement thresholds and the correct imaging methods. The current suggestion with regards to its aetiology will also be covered and the prevalence rates in different populations. The association between osteitis pubis and FAI will be addressed including current findings within the bioarchaeological literature.

3.1. Defining cam morphology

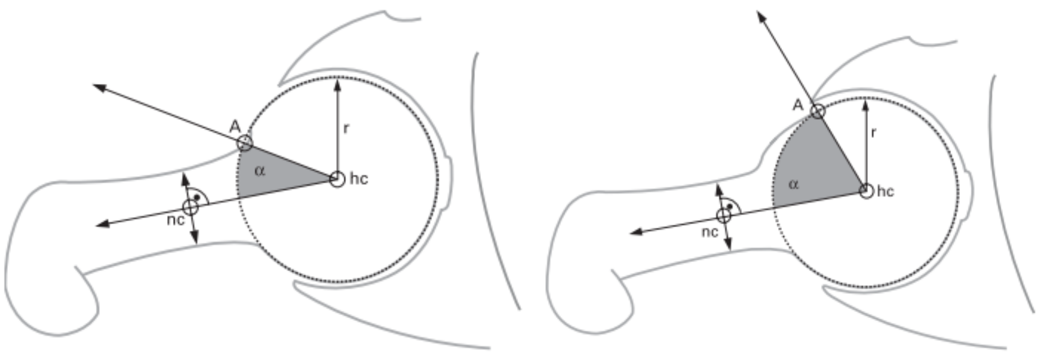
Cam morphology was first identified by Murray (1965) as a 'tilt-deformity' in relation to osteoarthritis of the hip. It was suggested that minimal undetected epiphysiolysis in childhood can go on to become this "tilt deformity" in adolescence/adulthood (Murray, 1965). Later, Stulberg et al. (1975) used the term "pistol grip deformities" to describe a mild deformity of the proximal femur and proposed to be due to unrecognised slipped capital femora epiphysis. Various terms have been used to described cam morphology throughout the literature such as "asymptomatic and symptomatic FAI", "tilt" or "pistol grip deformity" (Nepple et al., 2015). In 2016, the Warwick Agreement was convened to form international consensus on the correct diagnosis and management of patients with FAI (Griffin et al., 2016). Within this agreement, it was decided that a universal standard terminology was required to avoid confusion and therefore FAI syndrome is to be used to describe symptoms, clinical signs and imaging findings when observed concurrently, while the term 'cam morphology' is to be used to describe those individuals without appropriate symptoms and clinical signs but observable radiographic features (Griffin et al., 2016).

Various measures for the determination of the presence of cam morphology on medical imaging have been developed. These include both quantitative and qualitative measures. The most commonly used quantitative methods of determining the asphericity of the femoral head caused by the cam morphology include alpha angles and offset measurements. While qualitative methods have been used by Laborie et al.

(2011), describing cam morphology on AP and frog-leg view radiographs as "a marked loss of the wasting of the femoral head-neck junction and flattening of the normal concavity", "a focal prominence of the femoral neck", "a convex bump to the neck" or "flattening of the lateral aspect of the femoral head".

Alpha (α) angle measurements

The alpha angle is the most commonly used measurement to clinically determine the presence of cam morphology (Frank et al., 2015). Nötzli et al. (2002) developed this method of measuring femoral head asphericity on magnetic resonance (MR) scans to form standardised criteria for the identification of abnormalities at the femoral head-neck junction. In their study, Nötzli et al. (2002) compared the concavity of the femoral head-neck junction on the axial oblique MR scans of 39 patients with groin pain, limited internal rotation and a positive impingement test, to 35 asymptomatic controls. They found clear differences in mean α angles between the symptomatic and asymptomatic patients; 74.0° ± 5.4° and 42.0°± 2.2°, respectively. Figure 3-1 shows the method developed by Nötzli et al. (2002) to measure alpha angles for femora with and without cam morphology.



(a) (b)

Figure 3-1. Image from Nötzli et al. (2002) showing alpha angle measurements on a hip (a) without cam morphology and (b) with cam morphology.

Since this study, alpha angles have been used throughout the literature yet there is much disagreement regarding the appropriate cut-off values, imaging modality and location on the femoral neck to correctly determine the presence of cam morphology, Table 3-1 gives examples from the literature showing the different diagnostic cut-off values and average alpha angle values. A systematic review of the literature by Dickenson et al. (2016b) found the alpha angle cut-off values, for determining the presence of cam morphology, ranged from 50.5° to 83° within the 30 studies that met their inclusion criteria. In addition to this, different alpha angle thresholds have been suggested for symptomatic vs asymptomatic and males vs females. This wide range of cut-off values used by different studies and varying imaging modalities makes comparisons of prevalence rates of cam morphology within the literature difficult to achieve.

Although three dimensional imaging (MRI or CT) is the gold standard for determining the presence of cam morphology, several studies have determined alpha angle threshold values using various radiograph orientations (Nepple et al., 2012). Plain radiographs are commonly used for the initial diagnostic examination of the joint, as they are cheaper and faster to produce. Several authors have therefore determined thresholds using plain radiographs of varying orientations; Dunn view (Allen et al., 2009; Beaulé et al., 2012) and AP view (Gosvig et al., 2007; Agricola et al., 2014b).

Table 3-1 Diagnostic threshold and average alpha angle values from the clinical literature

Author	Sample information	Imaging modality	Diagnostic threshold	Average α angles
Nötzli et al. (2002)	39 patients with groin pain, limited internal rotation and a positive impingement test 35 asymptomatic controls	Axial oblique MR scans	-	Symptomatic: 74.0° ± 5.4° (55° to 95°) asymptomatic: 42.0° ± 2.2° (33° to 48°)
Pollard et al. (2010a)	83 asymptomatic volunteers- no clinical or radiographic evidence of hip disease or osteoarthritis 44 females, 39 males	Cross-table lateral radiographs taken in 15° internal rotation	≥63°	Males: 48°± 8° Females: 47°± 8° Overall: 47°± 8°

Agricola et al. (2014b)	1411 hips in 723 individuals from the CHECK cohort, with symptoms of early osteoarthritis between 45-65 years, 1468 hips in 734 individuals from the Chingford cohort, asymptomatic women aged 44-67 years	AP radiographs	60° for presence of cam Pathological threshold of 78°	
Barrientos et al. (2016)	101 asymptomatic volunteers, (41 males, 60 females), mean age 36.1 years ± 14.4 38 symptomatic patients undergoing surgery for FAI, (21 males, 17 females) mean age 36.12 years ±11.82	Oblique axial CT scans	57°	Asymptomatic: 47.8° ±5.3° Symptomatic: 66.8° ±12.2°
Fraitzl et al. (2013)	339 radiographs of asymptomatic individuals (170 males, 169 females)	AP and lateral radiographs	Men on AP and Lateral radiographs: 70° Women on AP radiographs: 61° Lateral radiographs: 66°	Men: AP 49.4°± 10.5° Lateral 49.1° ± 10.6° Females AP 45.0° ± 8.0° Lateral 46.1° ± 9.9°

The use of radiographs to measure alpha angles has been criticised as cam morphology typically presents anterosuperiorly and therefore it is often missed on AP and lateral radiographs (Ito et al., 2001). Additionally, due to the differing orientations of each radiographic view, it was suggested that this may affect the alpha angle size being recorded. Meyer et al. (2006), Monazzam et al. (2013) and Gosvig et al. (2007) tested this theory. Meyer et al. (2006) found in the same femur alpha angle measurements varied by 30° dependent on the radiographic projection used. Figure 3-2 is from Meyer et al. (2006)'s article showing the alpha angle measurements for each of the radiographic projections. Using a dry-bone cadaveric analogue AP radiographs were taken at 60°, 40° and 20° internal rotation as well as 0° (neutral rotation), 20°, 40° and 50° external rotation, Monazzam et al. (2013) found rotation of the femur accounted for approximately 58% of variation in recorded alpha angle size. Alternatively, Gosvig et al. (2007) found consensus between lateral and AP radiographs.

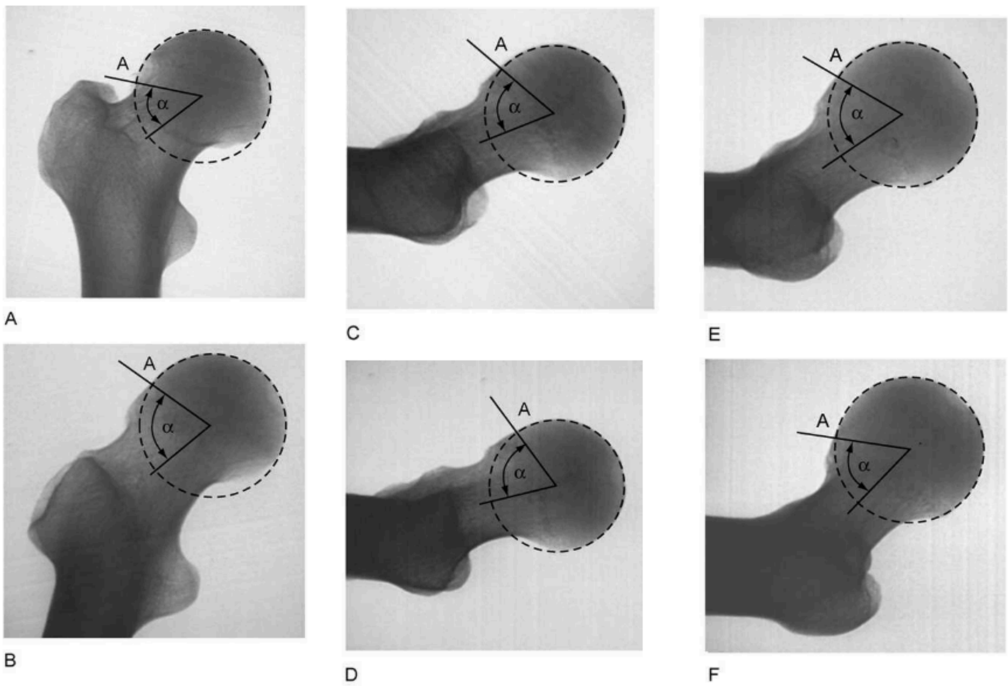


Figure 3-2 alpha angles recorded on radiographic projections (A) standard AP view, (B) Dunn view in 45° hip flexion, (C) standard Dunn view, (D) cross-table view in 15° internal rotation, (E) in neutral rotation, and (F) in 15° external rotation, From Meyer (2006)

The increased use of plain radiographs, due to the previously mentioned reasons, meant various studies (Barton et al., 2011; Nepple et al., 2012; Meyer et al., 2006; Gosvig et al., 2007; Dudda et al., 2009) have been carried out to determine if there is a difference in alpha angle measurements dependent on the imaging modality and projection used. Dudda et al. (2009), Barton et al. (2011) and Nepple et al. (2012) compared three-dimensional imaging (MRI/CT scans) to various radiographic projections taken in the same individuals to determine if there was a difference in alpha angle size, and ability to detect cam morphology, between these imaging modalities. Dudda et al. (2009) reported an underestimation of femoral head asphericity when using standard radiographs (AP pelvis and lateral cross-table views) compared to radial MRA slices. Barton et al. (2011) also showed measurements on AP radiographs to underestimate head asphericity. They did demonstrate a strong correlation between Dunn view radiographs and axial oblique MRI for alpha angle values. Overall, they recommend the use of MRI or CT due to the multiplanar capability of these imaging techniques, enabling them to determine the presence of cam morphology even with the variation in its location along the femoral head-neck junction (Barton et al., 2011). Nepple et al. (2012) compared radial oblique reformatted CT scans with radiographs of four projections; AP pelvis, 45° Dunn, frog lateral and cross-table lateral, in the same patients. The results showed in 61% of hips, all plain radiographic views had a greater maximum alpha angle than the CTs. Using a combination of all four radiographic projections, they showed that there was 90% sensitivity to the detection of cam morphology. The Dunn view had the highest sensitivity of the radiographic projections at 80%, while the frog lateral view had the best specificity at 91%. Unlike the previous studies, Nepple and colleagues recommended that AP pelvis, 45° Dunn and frog lateral radiographs can be used to accurately determine the presence of cam morphology.

Femoral head-neck offset measurements

Another commonly used measurement to determine the presence of cam morphology is femoral head-neck offset. This was initially described by Eijer et al. (2001) in their study attempting to determine if there was a difference in anterior head-neck offset between those with or without hip pain. On cross-table lateral radiographs head-neck offset was determined by measuring the distance between a line along the anterior cortex of the neck (line 2) and another line along the apex of the contour of the femoral head (line 3), with both lines parallel to the neck axis (line 1) (see Figure 3-3). The anterior head-neck offset ratio (OSR in this study but AOR in other studies) was than calculated by dividing the distance between the two lines (AOS) by the diameter of the femora head. They found the symptomatic group had a significantly smaller AOS and OSR than the asymptomatic group, 7.2mm ± 2.7mm to 11.6mm± 2.3mm (AOS for symptomatic group to asymptomatic group) and 0.13 ± 0.05 to 0.21 ± 0.03 (OSR for symptomatic group to asymptomatic group) respectively (Eijer et al., 2001).

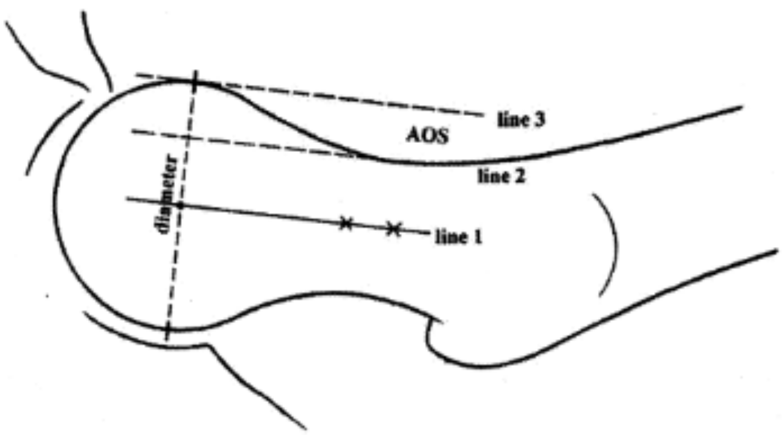


Figure 3-3. Femoral head-neck measurement, image from Eijer et al. (2001)

A threshold of ≤0.17 is commonly used as the cut-off for determining the presence of cam morphology (Nepple et al., 2014). Various studies have however questioned this threshold due to values found to be lower than this in asymptomatic populations. For instance, in their study Fraitzl et al. (2013) found the average AOR (anterior head-neck offset ratio) to be 0.15 ± 0.03 and 0.17 ± 0.04 for men, and 0.16 ± 0.03 and 0.18 ± 0.04 for females on AP and lateral radiographs respectively. Beaulé et al. (2007), observed threshold values of ≤0.15. They determined this pathological threshold by measuring AORs on cross-table lateral radiographs of 51 patients with symptoms consistent with FAI and positive impingement signs. In hips with an alpha angle ≥50.5°, the mean AOR was 0.13 which was significantly lower than those with an alpha angle <50.5° at 0.18. They suggest a hip with an AOR of ≤0.15 had a 9.5-fold increase in relative risk of having cam morphology based on an alpha angle ≥50.5°. This study has limitations of sample size with only 56 being measured and of these 45 having an alpha angle of ≥50.5°. Similar to alpha angle measurements the use of various different radiographic view makes it difficult to make comparisons between different studies and determine the most appropriate thresholds.

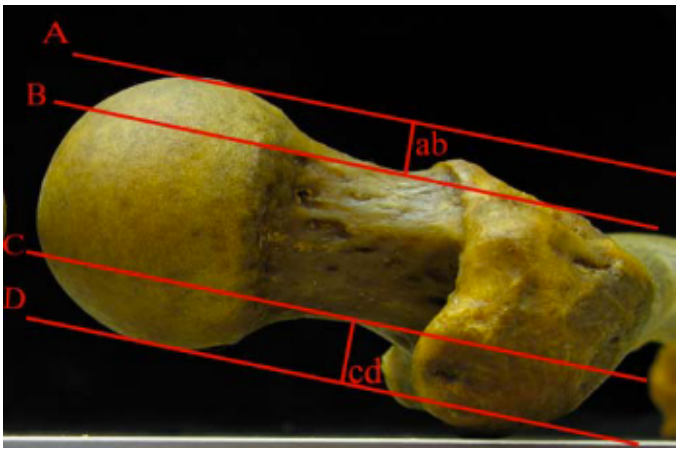


Figure 3-4 AOS/POS measurement, image from Toogood et al. (2009)

Toogood et al. (2009) extended the AOS measurement developed by Eijer et al. (2001) to calculate the anterior-posterior head-neck ratios (AOS/POS) on digital photographs in standardised orientations, see Figure 3-4. The posterior offset (POS) measurements were taken in the same way as the AOS measurements with all lines, both anterior and posterior, being parallel to the femoral neck axis. The AOS/POS ratios allow quantitative assessment of the head-neck translation. An AOS/POS ratio of 1 means the offset is equal with minimal translation. An AOS/POS of >1 means more anterior translation, while an AOS/POS of <1 suggests a more posteriorly translated femoral head on the neck axis (Toogood et al., 2009). This method allows for anthropometric variation between individuals which AO does not.

Toogood et al. (2009), found the mean AOS/POS was 1.14 ± 0.40 and the mean alpha angle was 45.61° ± 10.46° for their sample of femora from the Hamann-Todd osteological collection. They also found that as the AOS/POS ratio increased the alpha angle decreased, suggesting with increased anterior translation there is increased anterior concavity (Toogood et al., 2009). Nemtala and collagues also used AOS/POS ratios to analyse the proximal aspect of the femur, however, in their study they compared the ratios between individuals with FAI, due to cam morphology, and those without. Nemtala et al. (2010) reported a mean AOS/POS ratio of 0.56 ± 0.1 for the symptomatic group and 0.9 ± 0.2 for the asymptomatic group. This is the first study to measure AOS/POS ratios by Toogood and colleagues on medical imaging. The small sample numbers of only 15 symptomatic patients and 15 asymptomatic volunteers and the low interobserver correlation coefficient are limitations of this study. Zeng et al. (2016) used AOS/POS ratios in their study of the association between hip morphology and osteoarthritis. Using 3D reconstructions of CT scans, they compared patients without any abnormalities or degenerative changes at the hip to individuals with mild-to-moderate bilateral osteoarthritis of the hip. Similarly to Nemtala et al. (2010), this study found the AOS/POS ratio was smaller for the pathological group when compared to the ‘normal’ group. The results from these studies suggest the femoral head orientation is likely to be an impacting factor on alpha angle size and therefore should be considered. The higher interobserver agreement shown by Zeng et al. (2016) in comparison to Nemtala et al. (2010) suggests this method is more suited to use on osseous specimens or 3D reconstructions than cross-table lateral radiographs.

3.2. Aetiology

The true aetiology of cam morphology is still much debated within the literature. Several conditions leading to the slight deformities of the hip that can go undetected have been suggested as a cause, including; development hip dysplasia, slipped capital femoral epiphysis, Legg-Calvé-Perthes disease (Ganz et al., 2008).

Physical activity

High levels of physical activity is the most commonly suggest aetiology for cam morphology. It has been suggested male athletes are 1.9 to 8.0 times more likely to develop cam morphology than non-athletic controls (Nepple et al., 2015). Several studies have shown individuals who participate in high-levels of physical activity typically have higher alpha angles and therefore higher prevalence rates of cam morphology than non-athletes. For instance, when comparing semi-professional soccer players to amateur players, Lahner et al. (2014b) showed the distribution of alpha angles was correlated with the level of activity, based on training hours per week. In a further study, they showed the mean alpha angle size was significantly higher for athletes (top ranking track and field athletes) compared to non-athletic controls (52.2° ± 7.29° vs 48.1° ± 5.45°) and 34% of the athlete group had cam morphology present compared to only 2.7% of the control group (Lahner et al., 2014a).

Before and during skeletal maturation

The higher levels of loading, as well as the frequency and rigorousness of the movements at the joint in athletes compared to non-athletes, is the believed link between the development of cam morphology and physical activity. This has been found to be particularly the case during skeletal maturation. This concept was initially hypothesised by Murray and Duncan (1971) due to observations of hip osteoarthritis in younger individuals involved in mandatory athletics. Since then several studies have supported this concept through measures of cam morphology pre- and post-epiphyseal closure (Siebenrock et al., 2011; Philippon et al., 2013). The epiphyseal growth plate is a very dynamic area prior to complete fusion. In addition to this the developing skeleton is also more susceptible to the effect of forces and repetitive loading applied during intensive athletic activity (de Silva et al., 2016). Siebenrock and colleagues have published several studies looking into this association for different sports (Siebenrock et al., 2004; 2011; 2013a,b). Siebenrock et al. (2011) compared MRI scans from 37 male basketball players between the ages of 9 to 25 years, with 38 age-matched asymptomatic non-athletic controls. Those in the athletic group had uninterrupted participation in the training program since the age of 8 years old. In this study the mean alpha angles were greater in the athlete group (60.5° ± 9°) compared to the non-athletic controls (47.4° ± 4°). After epiphyseal closure 98% of athletes and only 9% of controls had an alpha angle >55°. When comparing alpha angle size before and after epiphyseal closure only the athlete group showed a change in mean alpha angle size. It was hypothesised this could be caused by a combination of high skeletal stress from vigorous exercise and differences in the direction of loading on the femur during this growth period leading to the development of cam morphology (Siebenrock et al., 2011). Following this study, Siebenrock et al. (2013b) compared the hips of 77 elite male ice hockey players, of which 43 had closed epiphysis and 34 had open epiphysis. This study found an increase in the mean alpha angle at the anterosuperior head-neck portion in those hips with closed epiphysis in comparison to those with open epiphysis (58.2° vs 49.1°). This however varies depending on the location the measurement was taken, for instance, at the 9 o'clock and 10 o'clock positions hips with a closed epiphysis had a significantly lower alpha angle size than those with open epiphysis. Fifty six percent of hips with closed epiphysis had an alpha angle of ≥55° while only 6% of hips with open epiphysis had an alpha angle of ≥55° (Siebenrock et al., 2013b). This study was limited by a relatively small sample size of 77 athletes and the lack of a control group of non-athletes for comparison.

Philippon et al. (2013) supported the results from Siebenrock and colleagues' research. They reported a significantly higher alpha angle in high-level youth ice hockey players when compared to a control group of youth skiers. With 75% of the ice-hockey players showing an alpha angle ≥55° compared to 42% of the control group. Although equal amounts of time was dedicated to each sport, ice-hockey players and skiers were compared due to differences in movements and use of the hip in the different sports. Unlike skiing, Ice-hockey involves repeated hip flexion and internal rotation that have previously been movements associated with the development of FAI. The ice hockey players were further divided into three age groups, 10-12 years ('Peewee hockey players'), 13-15 years ('Bantam hockey players') and 16-19 years ('Midget hockey players') to determine the alpha angle size based on epiphyseal closure. For those in the 10-12 years category all proximal femoral epiphyses were open, in the 13-15 year group the epiphyses were closed and open, while for the 16-19 years group all epiphyses were closed. There was a significant correlation between age and alpha angle size. Further to this the only group of ice hockey players with significantly more individuals with an alpha angle ≥55°

compared to their age-matched controls was the 'midget' group (the oldest group with only closed epiphyses).

Following the discoveries of the increase in alpha angle following epiphyseal closure Agricola et al. (2012) observed the proximal growth plate was extended into the neck more than usual prior to epiphyseal fusion. Therefore, it was suggested this extension of the growth plate could be a precursor to the development of cam morphology. This association was supported in a further study by Agricola et al. (2014a) and a later study by Siebenrock et al. (2013a). The latter showed epiphyseal extension was increased in athletes compared to non-athletic controls in their study of male elite basketball players (age range 9-22 years). Epiphyseal extension was recorded in individuals with an open epiphysis, while increased alpha angle size was typically seen after closure of the growth plate suggesting this epiphyseal extension could be a cause of cam morphology development (Siebenrock et al., 2013a).

Post skeletal maturation

Previous studies have looked at the development of cam morphology at the time of epiphyseal closure, however few studies have attempted to determine if the alpha angle size remains consistent after skeletal maturation in athletes. One such study, using a semi-quantitative scoring system, by Agricola and colleagues, analysed changes in the presence of cam morphology during and post maturation. They compared the radiographs of pre-professional soccer players (n=63) to follow-up radiographs approximately 2 years later. This study was the first of its kind comparing the presence of cam morphology on baseline and follow up radiographs. In the hips that had an open epiphysis at the baseline, the number with a prominence present increased from 2.1% to 17.7% at follow-up. While for those hips with closed epiphysis at baseline, there was no difference in the prevalence of prominences present at follow up, based on the visual classification system. For the whole group the alpha angle size increased from 59.4° to 61.3° and the prevalence of cam morphology (cut off >78°) increased from 7.9% to 13.5%. It was however only the hips with open epiphyses at baseline that showed an increase in the prevalence of pathological cam morphology at follow-up (Agricola et al., 2014a). In this study Agricola and colleagues also described the development of a cam morphology based on visual assessment. From 12 years to 14 years it went from concave to flattened, followed by the development a prominence on the anterior aspect of the femoral head neck junction from 14 years until epiphyseal fusion (Agricola et al., 2014a). The lack of significant increases in both alpha angle size and visual changes in those with closed epiphyses confirms the findings by many previous studies, that the formation of cam morphology is potentially during skeletal maturation. Other prospective studies in skeletally mature individuals agree with this finding. Gala et al. (2016) compared the mean alpha angle size of ten patients with cam morphology and thirteen with no evidence of cam morphology between MRIs (or CTs) taken a mean of 5.3 years apart. There was no significant difference in alpha angle size over the 5.1-year period for the individuals with radiological signs of cam morphology (48.7°±7.6/62.5°±9.2 vs 51.7°±7.7/61.5°±9.1) and those without (36.9°±6.7/47.4°±7.0 vs 39.2°±6.9/49.0°±9.6) when the initial MRIs were taken. Although it is not significant there is a slight increase in alpha angle size for both groups from the initial image to the follow up. They suggest this slight change could be due to measurement error due to the small difference however it is unclear if even a minor increase could have clinical relevance (Gala et al., 2016). It is therefore unclear if cam morphology does progress post-epiphyseal fusion. The small sample size in the study by Gala et al. (2016) is a limitation to these findings. Further studies are required to confirm these findings.

Arguments against physical activity

The findings of the study by Johnson et al. (2012) however, disagrees with the theory physical activity has a significant impact on alpha angle size. They compared the radiographs of fifty athletes who had participated in youth soccer at the ages of 10 to 14 years, for the males, and 8 to 12 years, for the females, to non-athletic controls. They found no significant difference between the groups for the prevalence of cam morphology or average alpha angle size. This study found participation in high-level sports (in this case soccer) during childhood does not cause an increased risk cam morphology and therefore does not affect the developing femur any differently to non-athletic individuals. They therefore suggest the higher recorded prevalence rates of cam morphology in athletes is because they are more likely to be symptomatic due to more vigorous movements at the joint (Johnson et al. 2012). Furthermore, a cross-sectional study by Carsen et al. (2014) compared the morphology of the hip in those with open and closed epiphyses in non-athletes. The volunteers for the study were from a fracture clinic at Children's Hospital of Eastern Ontario. The study found cam morphology was present in the closed epiphyseal group (cut-off value of ≥50.5°) and the mean alpha angle was greater in the closed group (at 1:30 position 50.18° ± 4.08°) compared to the open group (45.28° ± 7.05°), therefore cam is present in children who are not athletes. An activity score was however calculated from the Habitual Activity Estimation Score, a self-reported record of activity throughout the day. With regards to physical activity males in the closed group with cam morphology had significantly higher levels of activity. Epiphyseal status was not determined by observations on imaging but rather through the age brackets under normal circumstances the growth place would be closed (15-18 years in males and 14-18 years in females) this therefore may have affected these results.

Most of these studies used alpha angles to determine the presence of cam morphology. Agricola et al. (2012) suggested the use of alpha angles for determining the presence of cam morphology in individuals when the growth plate is unfused is inaccurate. They observed the contour of the femoral head appearing more oval shaped when the anterosuperior portion is unfused causing a higher alpha angle measurement. Moreover, they suggested the cam morphology is not fully visible until after fusion.

Genetics

Another suggested factor with regards to the cause of cam morphology is genetics. There are however few studies focused on whether there is a genetic predisposition to cam morphology. One such study by Pollard et al. (2010b) compared the hips of the siblings of patients being treated for FAI compared to a non-genetically related control group. They found a significantly greater prevalence of cam deformity in the siblings of those with FAI than the control group. Although this does suggest a possible genetic cause, the environmental factors cannot be completely disregarded if they were raised in the same manner. Pollard and colleagues incorporated the UCLA (University of California, Los Angeles) activity score to compare the activity levels of the sibling and the control groups. This method of scoring activity only assessed the activity score of the individual at the time of the study and the highest intensity exercise on a 10-point scale regardless of frequency. This limited understanding of activity during childhood, when many studies have suggested cam morphology is likely to develop and frequency of participation in physical activity. In addition to this, in this study Pollard and colleagues only compared activity scores between the sibling group and the controls not the test subjects (those with cam morphology) and their siblings. This would allow the possibility of determining if the greater prevalence of cam morphology in the siblings compared to the controls is due to environmental factors (equivalent activity in siblings) or genetics.

Applications

It is clear from this review that certain physical activities play a role in the development of cam morphology, particularly during skeletal development. It is possible genetics also has an involvement in its development however there are few studies currently available to confirm this. The link between cam morphology and physical activity has led to the assumption, by Lawrence et al. (2018), that cam morphology has applications to bioarchaeological study as indicative of habitual activity and therefore can be used to infer the sexual division of labour and socioeconomic differences in archaeological populations. It is currently difficult to determine if cam morphology can be used as an indicator of activity in past populations as it has not been widely studied in this context. Additionally, cam morphology and FAI have not been broadly studied with regards to occupational activity, with the prime focus on athletic activity in modern populations. Jochimsen et al. (2019) and Coppack et al. (2017) have focused on FAI and cam morphology in military occupations however there is currently no other studies analysing the rates of cam morphology in other occupations of differing activity levels. Furthermore, this review of the literature has shown there is a link between the development of cam morphology during epiphyseal fusion. It is unclear however if cam morphology continues to develop following epiphyseal closure due to the small sample sizes in the few studies focused on this e.g. Gala et al. (2016). If cam morphology remains constant following fusion, activity levels in adults will have limited impact on its development. This study of occupational physical activity in adults can therefore add to the understanding of the development of cam morphology. This will contribute to bioarchaeological through determining if cam morphology can be used in the analysis of skeletal populations as a marker of activity. Additionally, the comparison of occupations of varying activity levels will also add to the understanding of the development and adaptation of cam morphology in adults therefore having both clinical and bioarchaeological applications.

Not only does increased knowledge of the impact of occupational activity on the development of cam morphology have applications to these disciplines but the ability to determine the presence of cam morphology on skeletal remains has applications to both bioarchaeology and forensic anthropology, as described in 2.3.1. This includes acting as an additional identifying feature in victim identification and, potentially, to determine activity levels of past populations.

3.3. Prevalence

Varying prevalence rates for cam morphology have been reported in the literature due to use of differing imaging modalities and uncertainty towards diagnostic cut-off values, as highlighted in the previous sections. In addition to this, many studies also focus on specific population demographics such as; athletes vs non-athletes, symptomatic vs asymptomatic.

Rates from population-based studies

The true prevalence rates of cam morphology in the general population are not well understood as not all individuals with cam morphology develop FAI and therefore it can go undetected. There has however been a small number of population-based studies to determine this prevalence rate. In their US population based longitudinal cohort study Raveendran and colleagues included a total of 5,192 hips from 2,596 individuals to provide prevalence-based estimates of hip morphologies. They reported unilateral cam morphology (based on alpha angle threshold of >60° on AP radiographs) was present in 18% of males and 7% of females, while bilateral cam morphology was present in 9% of males and 3% of females. Additionally, the overall prevalence of cam morphology, based on alpha angles and the presence of a triangular index sign as defined by Gosvig et al. (2007), was approximately 25% for men and 10% for women (Raveendran et al., 2018). The study was however limited by the of use radiographs alone, while CT and MRI are more sensitive at detecting these morphological changes. All women were over the age of 50 years and therefore it is likely the prevalence rates for women is underestimated (Raveendran et al., 2018).

To determine the prevalence of cam morphology in asymptomatic males Reichenbach et al. (2010) analysed the MRI scans of individuals undergoing conscription for the Swiss army. In Switzerland, approximately 97.5% of males are required to attend a recruitment session and therefore this sample was a good representation of the young male population. A total of 179/244 of those that had MRIs showed evidence of cam morphology (based on a semi-quantitative scoring system). They reported an overall prevalence of 24% of cam morphology in asymptomatic males. These studies are different from many previous studies attempting to determine the prevalence of different hip morphologies as the samples understudy were not from clinical settings.

Rates from studies of asymptomatic individuals from clinical settings

Several studies have however attempted to determine this prevalence in asymptomatic individuals from clinical settings. In their study of asymptomatic volunteers Hack et al. (2010) found 14% (28/200) had cam morphology on at least one hip (defined by alpha angle >50.5°) and when broken down by sex, males were more likely than females to have cam morphology present, 24.7% (22/89) v 5.4% (6/11). Jung and colleagues used a random sample of 380 patients with abdominal or pelvic CTs for their study to determine the prevalence of cam morphology in asymptomatic individuals and found a slightly lower prevalence rate. Cam morphology was defined using alpha angle cut-off values defined by Gosvig et al. (2007), with ≥83° indicating pathological, 60° to 82° for borderline and ≤68° was considered normal for men, while for women pathological was ≥57°, borderline was 51° to 56° and normal was ≤50°. They reported 13.95% (30/215) and 14.88% (32/215) of male hips, while 5.56% (30/540) and 6.11% (33/540) of female hips were deemed to have pathological and borderline cam morphology respectively (Jung et al., 2011). De Bruin et al. (2013) analysed 310 retrospective radiographs from patients being investigated for reasons other than FAI (with 262 patients, 522 hips being included following exclusion criteria). They found only 7.7% (40/522) of hips presented with radiological signs of cam morphology, 15.6% (31/199) of male hips, 2.8% (9/323) of female hips. The retrospective nature of this study however meant only AP radiographs were used and alpha angles were not measured. Due to these limitations the prevalence of cam morphology is likely to be underreported in this study (De Bruin et al., 2013).

Rates from studies of athletes & non-athletes

Although present in the general population, the prevalence of cam morphology has typically been found to be higher in athletes, Table 3-2 shows the rates of cam morphology for a sample of studies of non-athletes while Table 3-3 shows the rates for studies including athletes. In their systematic review of the literature Frank et al. (2015) found a ratio of 3:1 when comparing the presence of cam morphology in asymptomatic athletes to asymptomatic non-athletic controls (54.8% vs 23.1% respectively). Table 3-3 shows the recorded prevalence of cam morphology in various athletic populations. Several systematic reviews have looked at these prevalence rates within the literature. In their review of the literature Dickenson et al. (2016b) found the prevalence rate of cam morphology in different groups of athletes (both symptomatic and asymptomatic) ranged from 48% to 75% of individuals and 2% to 92% of hips. Nepple et al. (2015) only included studies involving; symptomatic or asymptomatic athletes, with >50% male participants and a control group. They found rates (by hip) of reported cam morphology in male athletes was 17% to 93% compared to 9% to 56% of male controls. Unlike the reviews by Dickenson et al. (2016b) and Nepple et al. (2015), Frank et al. (2015) only selected articles including asymptomatic individuals in their review of the literature. Reporting prevalence rates of 54.8% of athletes and 23.1% of non-athletic controls having asymptomatic cam morphology. Varying prevalence rates have been shown between different sports, believed to be due to the varying movements and forces required to perform the different activities. In a comparison between the prevalence of cam morphology on the kicking legs of asymptomatic male semi-professional and amateur soccer players Lahner et al. (2014b) found a prevalence rate of 62.5% for the semi-professional players (based on a threshold of >55°) compared to 27.3% for the amateur players. The overall prevalence of cam morphology was 59% (13/22) for the semi-professional group and 40% (9/22) in the amateur group. Larson et al. (2013) reported 75% (94/125) of American football players had radiographic cam morphology present (alpha angle >55°). Increasing alpha angle size was associated with increased symptom prevalence however the presence of cam morphology was not an independent predictor of symptoms (Larson et al., 2013). The study by Siebenrock et al. (2013b) analysed alpha angle size in elite ice hockey players between the ages of 9-36 years. In the individuals with closed epiphysis 56% of hips (24/43) had an alpha angle ≥55°.

The prevalence of cam morphology in athletes practicing martial arts, in particular capoeira was studied by Mariconda et al. (2014). They reported a prevalence rate of 45.8% of hips (22/48) (based on an alpha angle >60°) however a rate of 91.7% (44/48) of hips based on one radiographic sign of cam morphology (alpha angle >50° or head-neck offset <8mm).

Table 3-2. Prevalence rates of radiographic evidence for cam morphology in adult non-athletes

Author	Sample information	Cam α angle cut-off	Prevalence of cam, per individuals (%)	Prevalence of cam, per hips (%)
Johnson et al. (2012)	Non-athletic controls	≥55°	Overall: 44% Males: 56% Females: 32%	Not described
Jung et al. (2011)	Asymptomatic individuals	Men: Pathological ≥ 83° Borderline 69° to 82° Normal ≤ 68° Women: Pathological ≥ 57° Borderline 51° to 56° Normal ≤ 50°	NA	Men: Pathological: 13.95% Borderline: 14.88% Normal: 71.16% Women: Pathological: 5.56% Borderline: 33% Normal: 88.33%
Lahner et al. (2014a)	Non-athlete controls	>55°	Not described	2.7%
Reichenbach et al. (2010)	Males attending conscription centre	Semi-quantitative scoring system	73%	Not described
Khanna et al. (2014)	Volunteers	>50.5° ≥60°	21%	Not described

Table 3-3 cam morphology prevalence rates in athletes from the literature

Author	Sport and level	Cam α angle cut-off	Prevalence of cam, per individuals (%)	Prevalence of cam, per hips (%)
Silvis et al. (2011)	Professional and collegiate hockey players	>50°	39%	Not described
Kapron et al. (2011)	Collegiate football players	>50°	Not described	Frog-leg lateral: 54% AP view: 55%
Gerhardt et al. (2012)	Elite soccer players	>50°	Males: 68% Females: 50%	Not described
Johnson et al. (2012)	High-level youth soccer players	≥55°	48% Males: 60% Females: 36%	Not described
Larson et al. (2013)	Collegiate national football league players	>55°	75.2%	65.3%
Lahner et al. (2014a)	Elite track and field athletes	>55°	Not described	34%
Lahner et al. (2014b)	Semi-professional soccer players & amateur soccer players	>55°	Not described	Semi-professionals: 47.7% Amateurs: 29.5%
Mariconda et al. (2014)	Capoeira (Brazilian martial arts) players	>50°	Not described	91.7% with >50° 45.8% with >60°
Tak et al. (2015)	Elite football players	>60° Pathological cam: >78°	64% with >60° 29% with >78°	49% with >60° 18% with >78°
Farrell et al. (2016)	Elite rugby players	>50.5°	55%	Not described
Tak et al. (2016)	Professional soccer players	>60°	63%	50%
Larson et al. (2017)	Professional hockey players	>50°	Not described	85%
Fraser et al. (2017)	Dance athletes & non-dance athletes	>55°	Not described	Dance athletes: 18.3% Non-dance athletes: 42.3%

3.4. Association with Osteitis Pubis

Osteitis pubis is considered one of the most chronic and incapacitating conditions to affect athletes (Rodriguez et al., 2001). It is an overuse syndrome at the pubic symphysis causing pain and tenderness at this area. In athletes it is believed to be caused by microtrauma from repeated muscle strain at the pubic bones by the abdominal and adductor muscles however the actual aetiology is still unclear (Angoules, 2015). Additional causes however include pregnancy and parturition, rheumatic disorders, osteoarthritis and infections (Angoules, 2015). Through a review of the literature (please see appendices 1 for examples of studies used and imaging findings) the commonly reported radiographic indicators for osteitis pubis include; sclerosis, widening and vertical displacement, subchondral cysts, osteophytes, erosions and irregularity. Figure 3-5 demonstrates the difference between a pubic symphysis without (a) and with (b) osteitis pubis.

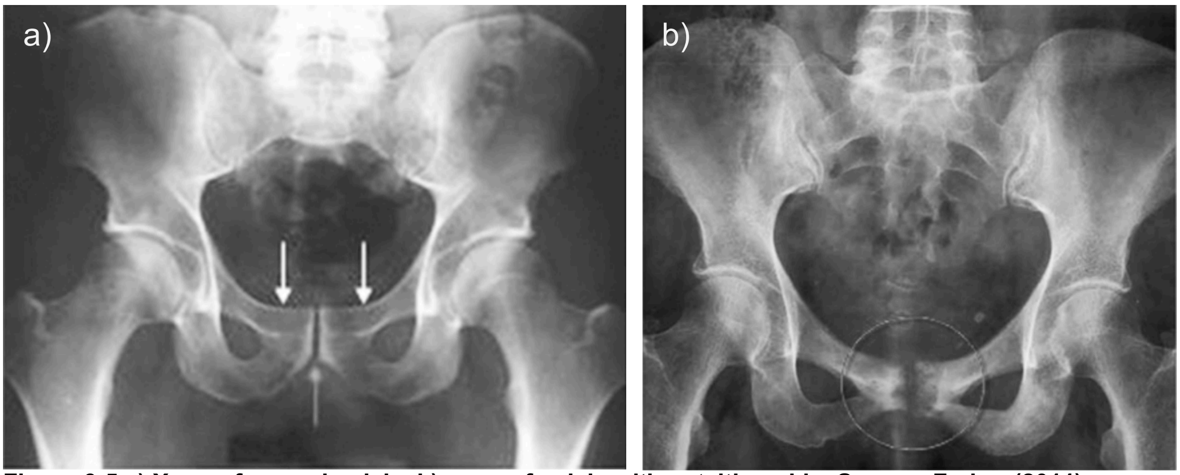


Figure 3-5 a) X-ray of normal pelvis, b) x-ray of pelvis with osteitis pubis. Source: Farber (2011)

Anatomy of the pubic symphysis

The pubic symphysis is a non-synovial fibrocartilaginous joint. It is formed by the two pubic bones and a fibrocartilaginous disk. The surfaces of the pubic bones which articulate with the disk are lined with a very thin layer of hyaline cartilage (Budak and Oliver, 2013). The symphysis connects the two weight bearing os coxae with the ligaments assisting in the maintenance of the mechanical integrity and prevent motion during everyday activities (Gamble et al., 1986). There are four main ligaments which reinforce the pubic symphysis; superior pubic (or suprapubic) ligament, inferior pubic ligament (or arcuate), anterior pubic ligament and the posterior pubic ligament (Gamble et al., 1986; Becker et al., 2010). Figure 3-6 illustrates the anatomy at this area. The joint is further stabilised by the many musculotendious structures which attach to the pubic symphyseal capsule (Budak and Oliver, 2013). These muscles include, the pyramidalis, rectus abdominis, gracilis, adductors, obturators and levator ani posterior (Gamble et al., 1986).

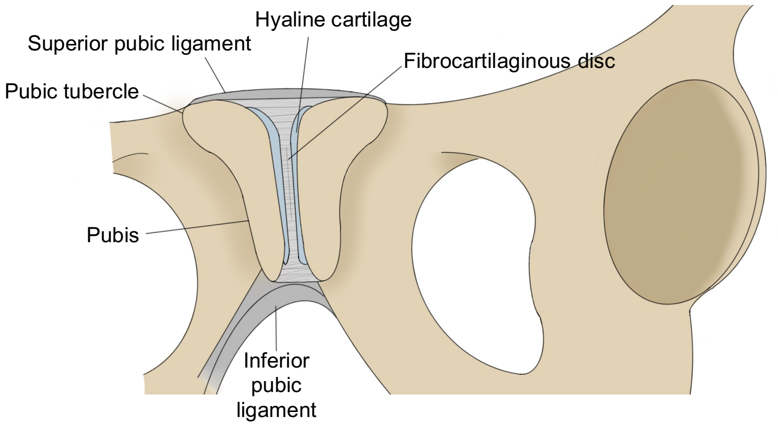


Figure 3-6 Illustration demonstrating the anatomy of the pubic symphysis. Image by E.Saunders

Aetiology of osteitis pubis

The pubis symphysis is capable of withstanding impact forces to the pelvis which occur in everyday activities such as walking or running. During normal gait, weight is transferred from one side of the pelvis to the other, with the forces centred on the pubic symphysis. When these movements are magnified and additional, more stressful, movements are applied it puts more biomechanical strain to the symphysis and supporting structures (Cunningham et al., 2007). Many authors agree that repetitive movements common in athletic activity such as kicking, rapid acceleration and sudden directional change cause stress to the pelvis which lead to bony stress reactions and osteitis pubis (Beatty, 2012; Budak and Oliver, 2013; Choi et al., 2011; Omar et al., 2008). Muscle imbalance has also been linked to osteitis pubis. The abdominal and adductor muscle groups act antagonistically. The abdominal muscles attach to the thoracic cage and the symphysis, acting to stabilize the symphysis. The adductor muscles act to move the lower extremity towards the symphysis, see Figure 3-7 (Mandelbaum and Mora, 2005). If there is imbalance between the actions of these two muscle groups the equilibrium of forces will be disrupted leading to microtrauma and tissue degeneration (Rodriguez et al., 2001). In addition to this, the chronic overuse of these muscles by many athletes is believed to lead to microtrauma (Angoules, 2015). In their study of medical personnel of Australian Football League clubs Pizzari et al. (2008) found that all personnel felt that osteitis pubis is an overuse injury due to imbalance between the loads placed on the pelvis and the integrity of the pelvic structures. These imbalances were thought to be due to internal factors (variables identified to be features of the player that reduce the ability of the pelvis to cope with these forces) such as; immature skeleton, hypermobility, hypomobility, intrapelvic asymmetry and technique deficits. External factors were also believed to play an important role (variables which are perceived to place greater load onto the pelvic) such as; training intensity and volume, kicking, trauma, change of direct, ground hardness and number of games played (Pizzari et al., 2008).

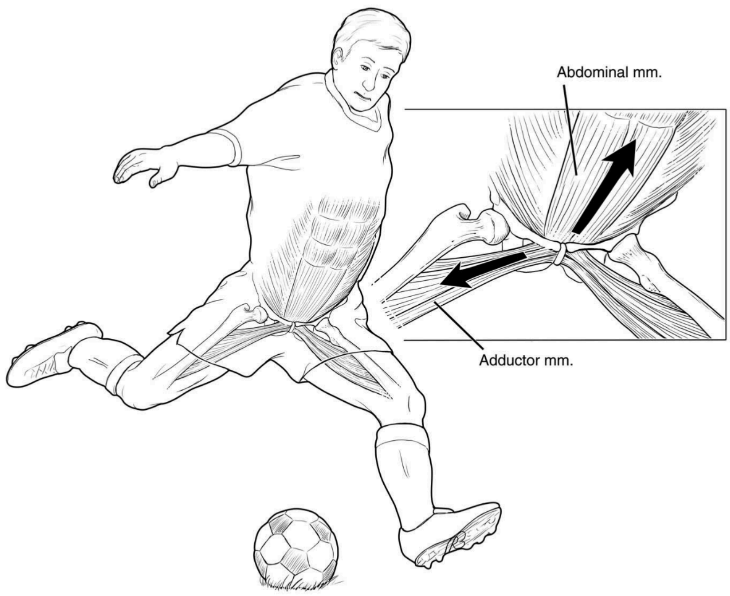


Figure 3-7 Image demonstrating the pull of the abdominal and adductor muscles at the pubic bones during kicking (Mandelbaum and Mora 2005)

Association between FAI and osteitis pubis

Association between FAI and osteitis pubis in athletes has been suggested by many authors (Phillips et al., 2016; Hammoud et al. 2014; Matsuda et al., 2015). It is proposed that restricted range of motion at the hip, due to an impingement, particularly internal rotation causes additional stress to the pelvic ring during turning and twisting motions (Angoules, 2015). Williams (1978) and Verrall et al. (2005) found that loss of hip mobility, particularly internal rotation, was present in all the patients with osteitis pubis in their series. It was not however clear if this reduction in range of motion precedes the development or is a consequence of osteitis pubis (Verrall et al., 2005). A later study by Verrall et al. (2007) found that lower hip joint range of motion precedes chronic groin injury. They postulated if an athlete has reduced range of motion of the hip this adds greater stress to the pubic symphysis leading to osteitis pubis (Verrall et al., 2007). Research has established that the presence of FAI causes loss of internal rotation of the hip, incorporating clinical tests of hip rotation in the clinical diagnostic tests (Griffin et al., 2016; Clohisy et al., 2009). This occurs due to the contact of the femoral neck with the acetabular rim earlier than in individuals without the impingement therefore limiting the range of internal rotation. This link between the two conditions is therefore unsurprising. Birmingham et al. (2012) investigated the effect of cam morphology on the motion of the pubic symphysis. Their cadaveric study using simulated cam morphology found motion of the pubic symphysis at the point of bony contact between the femoral head-neck junction and the acetabular rim. There was significantly more rotation of the pubic symphysis in those with cam morphology in comparison those without the simulated impingement (Birmingham et al., 2012). Their study suggests that in normal state, during internal rotation, there is motion at the pubic symphysis when the femoral neck contacts the acetabular rim. In those with cam morphology this contact occurs earlier than is required for activity and therefore more likely to become pathologic with repetitive strain (Birmingham et al., 2012). As with many studies of this nature there are several limitations, for instance the artificial cam morphology used in this study is not an exact anatomic representation and the small sample size of only twelve hips. Furthermore, this study also does not consider the normal effect of muscular stabilisation and action during motion.

Authors have reported athletic patients co-afflicted with osteitis pubis and femoroacetabular impingement (Larson et al., 2013; Matsuda et al., 2015). Matsuda et al. (2015) investigated the outcomes of treating FAI and osteitis pubis concurrently due to high prevalence of athletic patients with both osteitis pubis and FAI presenting at their practices. They recommend, although positive outcomes from treating both conditions, initial surgery for FAI followed by treatment for osteitis pubis, if symptoms persist. This is due to the belief that treatment of the FAI will reduce the stress transfer to the pubic symphyseal region therefore reducing symptoms of pubic pain (Matsuda et al., 2015). A study by Phillips et al. (2016) also supports the idea that there is a possible correlation between cam morphology and osteitis pubis in the general population not just in athletes. Their retrospective study allowed them to rate and compare radiographic changes at the pubic symphysis between a population of individuals diagnosed with FAI and age-matched controls without FAI. They reported a statistically significant increase in the prevalence of osteitis pubis in patients with cam morphology in comparison to the age-matched control subjects. Additionally, they found in those controls which displayed signs of osteitis pubis, the average severity was lower than in patients with FAI. Although present in most patients with FAI, osteitis pubis was classified as being minimal or mild. The author believes this to be likely due to the fact these patients are not believed to be elite athletes and are younger therefore the osteitis pubis is not likely to have increased in severity (Phillips et al., 2016). Due to the retrospective nature of this study the authors were unaware of clinical information and medical history including pain and occupation, limiting the study to only imaging results. As with many clinical studies the small sample size is also a limiting factor.

Osteitis pubis from a bioarchaeological and forensic perspective

It is important to understand any condition likely to impact the pubic symphysis due to the common use of this area in the formation of a biological profile, particularly for age estimation. At the time of this study however osteitis pubis has not been widely studied within the disciplines of bioarchaeology and forensic anthropology. Judd (2010) suggests that this under-representation may be due to three factors:

1. The pubic bones are often damaged or missing in many archaeological remains
2. The changes commonly seen in the early stages of osteitis pubis may have been confused for signs of ageing
3. The aetiology of this condition has remained unclear to many physicians.

In addition to these factors osteitis pubis may have previously been mistaken for signs of parturition in females and there also may have simply been an unawareness of this condition and how it affects the bone. Judd (2010), Pfeiffer (2011) and Gregg and Bass (1996) are the few articles which present case studies of suspected osteitis pubis they attribute to athletic activity. Table 3-4 includes the diagnostic features determined as possible osteitis pubis by each author, while Figures 3-8 and 3-9 are examples of these suspected cases from Pfeiffer (2011) and Judd (2010). These studies are the few which address this condition through analysis of skeletal remains. There are currently no studies which have attempted to form set recording criteria to determine the presence of this condition on bone. This limits the understanding rates in past populations and also restricts recognition of this condition when forming age estimations from this area of the skeleton.

Mays (2015) also highlighted the necessity for more awareness of how osteitis pubis affects pubic symphysis and the age estimation process. The formation of an age-at-death estimates from adult skeletal remains is described by Cunha et al. (2009) as “the Achilles’ tendon of anthropology” predominately due to the differences between physiological age and chronological age. In archaeological populations, age estimation is important for palaeodemography as well as interpreting other data obtained from the skeleton such as disease rates (Mays, 2015). Where incorrect, estimations can cause misinterpretation of population demographics as well as other results such as rates of disease per age group. While in forensic anthropology, the aim of age estimation is to help reach a positive identification through comparison to missing persons data. Although these estimates are given in age brackets, lack of accuracy can result in ruling out the correct individual (Cunha et al., 2009). Many of the osseous changes used to diagnose this condition radiologically mirror some of the traits which represent the later stages of many age estimation methods (Mays, 2015). This suggests it is possible individuals with this condition would more likely to be given an over estimate for their physiological age in comparison to their chronological age. For both disciplines it is therefore important to be aware of a condition which is likely to impact the accuracy of these results. Therefore, due to the possible association between osteitis pubis and cam morphology, to fully understand the contributions to bioarchaeology and forensic anthropology that can be made by FAI, it is also important to raise awareness of osteitis pubis and also analyse the pubic symphysis for changes associated with this condition.

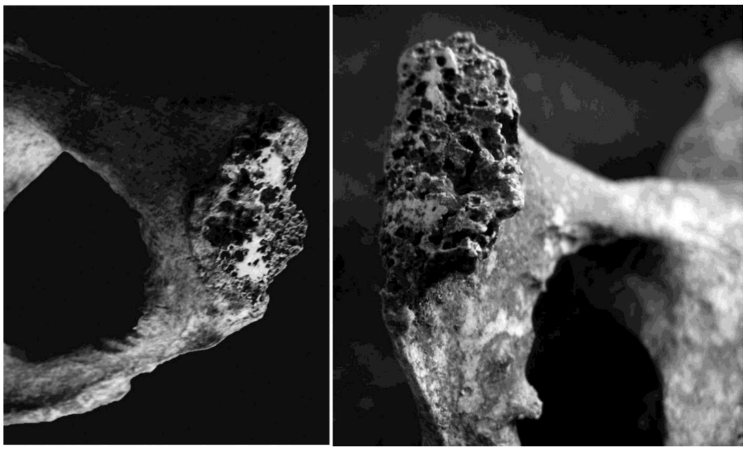


Figure 3-8 Left and right pubic symphyses with possible osteitis pubis. Source: Pfeiffer (2011)

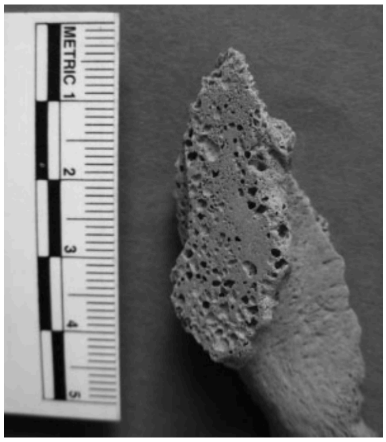


Figure 3-9 Right pubic symphysis with possible osteitis pubis. Source: Judd (2010)

Table 3-4 Possible cases of osteitis pubis recorded on archaeological populations

Author (date)	**Burial No.**	**Specimen**	**Diagnostic features observed on pubic bones**
Gregg and Bass (1996)	B29A	(1)	Pitting, bony spurs, changes to adductor longus and gracillis m. insertions
	B7B	(2)	Pitting on anterior pubic face, changes to rectus abdominus insertion
	B3E	(3)	Pitting, cystic changes at rectus abdominus m. insertion. Hypertrophy of superior and anterior portion of pubic bones.
	B6A	(4)	Pitting, roughened pubic bones, defaced. Insertion of left rectus abdominus m. most affected
		(5)	Pitting, roughened pubic bones, deformed, particularly the superior surfaces of rectus abdominis m. insertion
	B12D	(6)	Pitting, scarred pubic bones, multiple cystic spaces. Anterior erosion to pubic bones. Rectus abdominis, gracillis, and adductor longus m. insertions involved.
	B71E	(7)	Roughness, cystic degeneration, irregularity of pubic faces in area of rectus abdominis insertion
		(8)	Pubic symphysis rough, eroded, cystic changes in subchondral layer, in area of rectus abdominis and gracillis m. insertions.
	B94	(9)	Old fracture of the pelvis. Bone spur extending distally
		(10)	Deep pits, scarring, deformity with areas of cystic degeneration bilaterally. Insertions of the rectus abdominis and gracillis are involved
Judd (2010)	32		Pubic symphyseal faces completely flat and smooth with a sheen and macroporosity

Pfeiffer (2011)	NMB 1639	Pelvis skewed from midline. Auricular surface of right ilium is porous with slight eburnation. Osteophytes present on auricular surface. Left iliac auricular surface has porosity and is eburnated in the caudal region. Pubic faces both remodelled, osteophytes present. Right ventral surface showed smooth oval surface for attachment of gracillis, spicule of bone at attachment site for pectineus. Ventral half of right pubic has eburnation. The left pubis showed strong ridges at side of insertion of the gracilis tendon.

Chapter 4. Materials & Methods

This chapter will focus on the samples selected for this research and the methods used. The first section will focus on the samples and what makes them appropriate for study, starting with the CT samples, then the Wharram Percy collection and followed by the Luís Lopes collection. For both the skeletal collections contextual information will also be included. The inclusion of contextual information is vital when forming interpretations regarding the cause of osseous changes. Following this, the methods, will describe each of the methods used for data collection. A description of the statistical tests selected for use will be provided and finally, inter- and intraobserver error rates will also be provided for several of the methods used.

4.1. Ethics

This study was approved by institutional ethics (CURES) prior to data collection through submission of a full research proposal. Additional approval was obtained via GAFREC through Coventry and Warwick University Hospital trust research and development department prior to collection of the CT scans. All CT scans were anonymised prior to collection, with only age in years (date of birth excluded) and sex included. The research proposal for GAFREC approval was submitted and data collection was carried out through members of senior clinical staff from the hospital trust. All data was stored on an encrypted hard drive at all times. With regards to the skeletal collections, access was granted by the curators of the Luís Lopes collection and the Historic England Committee for the Wharram Percy collection following submission of a complete research proposal. The human remains were accessed and handled following instructions set by the curators for both collections. Care and respect was maintained at all times and BABAO code of ethics was adhered to.

4.2. Materials

4.2.1. FAI- and non-FAI groups, University Hospitals Coventry and Warwickshire (UHCW)

A sample of retrospective pelvic axially orientated CT scans were collected for eighteen individuals who had been undergoing investigation for FAI (termed the FAI-group) at the time the image was taken, and a random sample of twelve individuals, having CT scans taken for reasons unrelated to FAI, including trauma (termed the non-

FAI group). The scans for both groups were provided by consultant radiologists from the hospital trust and were grouped according to those being investigated for FAI and the random sample of controls. The scanner used was a GE 128 slice CT scanner. Information on when the scans were taken was not available as the scans were anonymised prior to collection, with only age in years and sex available. The retrospective nature of this sample meant there was no information on occupation or recreational activity was available as this is information is not typically recorded in patient demographics when imaging is taken, unless requested. This limited its use with regards to understanding more about the aetiology of this condition. In addition to this, no clinical information was available due to the requirement for anonymised data, consequently it was not clear which hip was under investigation for the FAI group or what type of FAI was being investigated (cam or pincer morphology).

The FAI group was included to provide a clinical comparison, due to the limited awareness of how FAI presents on skeletal specimens. While the non-FAI represents a sample of 'normal' hips to determine which changes are due to this condition. 3D volume rendered models were created from the axially orientated CT scans to allow the observable changes and measurements to be directly comparable to the skeletal collections and observations made on bone. This will be described further in section 4.3.2.

4.2.1.1. Sample analysed

Adults only were included (age >18 years) in this study. The average age for the FAI group was 41.6 years with a range of 36.0 years. While for the non-FAI group, the average age was 41.3 years with a range of 59.0 years. Males and females were included in both groups, with twelve males (24 femur) and six females (12 femur) in the FAI group, and seven males (14 femur) and five females (10 femur) in the non-FAI group. The demographic data for the number of individuals per age range category is shown in Table 4-1.

Table 4-1 Number of individuals per age range category by sex for FAI and non-FAI groups

Group	Sex	Age range categories			Total
		18-29 years	30-49 years	50+ years	
FAI	Males	1	8	3	12
	Females	0	4	2	6
	Total	1	12	5	18
Non-FAI	Males	3	3	1	7
	Females	1	1	3	5
	Total	4	4	4	12

4.2.2. Wharram Percy Skeletal Collection

The Wharram Percy skeletal collection is housed at Historic England, Fort Cumberland, Portsmouth. This collection represents one of the most widely studied and best known medieval villages in Britain (Sofaer Derevenski, 2000). The Wharram Percy skeletal collection encompasses around 900 years from mid-10th century to mid-19th century excavated from the church and churchyard (Mays, 2007a).

Over 900 skeletons were discovered in the church and churchyard with 687 of these being analysed and recorded (Mays et al., 2007). Figure 4-1 shows the plan of the churchyard with the seven excavated areas. The number of burials per phase include: CN, 39; EE, 98; G, 117; NA, 217; SA, 32; V, 52; WCO, 132. The assignment of phase was done through a variety of methods including; burials with radiocarbon dates, those datable by coffin fittings, stratigraphic relationships and burials from area of the churchyard with radiocarbon dating which had a restricted period of use. Each phase was assigned to the following time periods:

- Phase 1 – 950-1066 AD – Large Anglo-Saxon
- Phase 2 – 1066-1348 AD – Earlier medieval
- Phase 3 – 1348-1540 AD – Later medieval
- Phase 4 – 1540-1850 AD – Post medieval

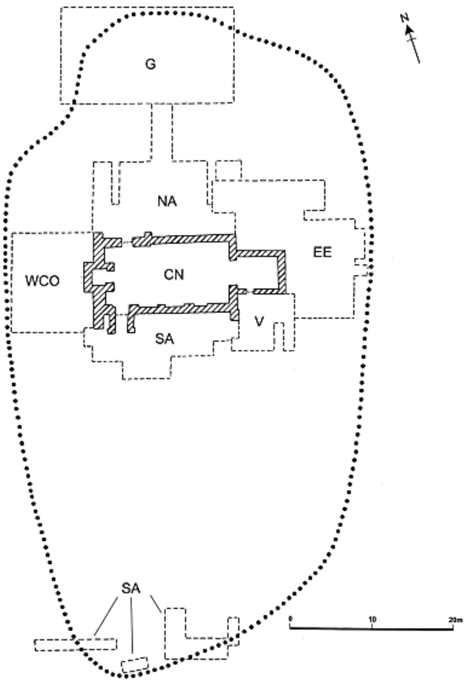


Figure 4-1 Excavation plan of the church and churchyard at Wharram Percy, from Mays et al. (2007)

The letter prefixes are not associated with antiquity, with the exception of the church naïve (CN) which is predominantly post medieval; EE, G and NA are predominantly late Anglo-Saxon to early medieval; SA and V are mainly from the late to post Medieval periods with some Late Anglo-Saxon to Early Medieval, while WCO was a mixture from all time periods (Mays et al., 2007).

4.2.2.1. Contextual Information

Wharram Percy is located in the Yorkshire Wolds. The medieval village was situated on the chalk plateau on the western side of the Wharram Percy valley. The church is positioned on an artificial terrace approximately 4.7m above the valley floor (Harding and Wrathmell, 2007).

The lives of peasants in medieval rural populations was strenuous for children, women and men. Children worked as soon as they were able and would begin chores such as collecting wood or food resources by the age of 5 years (Mays, 2007). Distinctions in tasks between males and females was shown in children as well as adults. This was highlighted by a coroner's report which described how in toddlers, boys died from accidents outside the home, such as while working in the fields, while girls were more commonly injured from accidents with pots or cooking items, during this period (Bennett, 1987). By adolescence they would have carrying out similar tasks to those of adults and therefore be subjected to high levels of mechanical stress through strenuous physical labour (Mays, 2007). Typically involved in low-skill tasks such as labourers, ditchers, hedgers and helpers (Bennet, 1987).

Males and females from rural medieval populations, such as the Wharram Percy collection, were believed to have been engaged in strenuous physical labour. The daily lives in a medieval rural population varied seasonally including ploughing in March and killing hogs in December (Judd and Roberts, 1999). In winter many peasants would have been involved in hunting and many households would have carried out additional tasks for additional income such as butchering, baking, timber production (Judd and Roberts, 1999). The sexual division of labour in these populations was therefore flexible in response to the varying demands of agriculture during the year (Bennett, 1987). Females would have domestic duties, however it is likely they also undertook a large amount of tasks similar to males (Agarwal, 2012). Men usually carried out the heavy labour tasks such as; ploughing, carting goods and felling trees (Bennet, 1987) and they were prohibited from performing female domestic tasks, however roles outside this arena where more fluid between the sexes (Sofaer Derevenski, 2000) Females maintained the household including gardening, dairying and raising poultry but they would also have assisted with tasks in the fields (Bennett, 1987). Women would assist with harvest during the peak seasons while during winter the men would carry out more tasks near to the home (Judd and Roberts, 1999).

Studies have analysed osseous changes of the Wharram Percy collection to infer the level of physical activity for this population and its sexual division. In their study, Sofaer Derevenski (2000) analysed a sample from Wharram Percy to compare activity-related osseous changes of the spine between males and females. They found only facet remodelling was statistically different between males and females, with a greater percentage in males suggesting greater load-bearing. The distribution pattern across the spine was similar between both sexes, suggesting a similar form and level of stress. The results of this study suggest similar daily activities between the sexes in this population based on osseous changes to the spine. Mays (2007a) considered activity patterns in the upper limb via humeral diaphysis cross-sectional morphology in the Wharram Percy Collection. No significant difference was found between males and females which implied little difference in the activities requiring heavy mechanical loading of the upper limb between the sexes (Mays, 2007a). The high level of osteoarthritis in the population is another indicator of the level of physical activity (Mays, 2007a). The distribution of osteoarthritis differed between the sexes, with the joints of the upper limb being more affected in males, and the joints of the legs and back in females. This suggests, although the distribution of heavy work was split evenly, males tended to be involved in more strenuous activity using the upper limb while females carried out more physically demanding work which placed mechanical stress on the lower limb and back (Mays, 2007a). A study by Judd and Roberts (1999) analysed fracture patterns in a rural medieval skeletal sample as a method of determining daily living and working environments. They compared their results to those from additional British medieval samples, including one rural and three urban, to determine if the activities carried out in farming differed from those in the urban setting. The high prevalence of fractures in women in this rural setting indicated a physically demanding lifestyle for women as well as men. Judd and Roberts suggested that the low rates of age-related fragility fractures in women could also suggest that the physically activity rural lifestyle may have protected against this. They also noted the presence of greenstick fractures suggesting it is likely children were involved in some of the physically demanding tasks associated with medieval farming life. When they compared the fracture frequency of the rural population to the urban they found urban females had a lower frequency than any other group. This is likely due to the differences in general activities between the groups and rural females were involved in more dangerous daily tasks than the urban females. This high level of physical activity for males, females and children is reason for this sample selection. In order to determine if cam morphology is associated with occupational physical activity the Wharram Percy collection represents a population that had very physically demanding occupations.

The rural economy at Wharram Percy varied over the large time span represented. Documentary evidence showed by the late 13th century the region was predominantly arable farming focused on wheat and barley (Oswald, 2004). Sheep and cattle also played a role however by the 16th century there was an increase in sheep farming due to the growth in the wool industry (Oswald, 2004). By 1773 records indicate there was however a land use from pasture back to arable. In addition to records the earthwork is indicative of cultivation and ploughing with the remains of medieval ridge and furrow cultivation surviving beyond the modern ploughing as well as possible indications of episodes of cultivation associated to the earliest forms of the village, pre-Norman Conquest (Oswald, 2004). Although there is a change in land use and the technology used, the work carried out here is consistently agricultural in nature and therefore potentially physically strenuous.

Juvenile death rates give an indication of the sanitation and medical care of a population. In the Wharram Percy collection 45% of the total burials were aged less than 16 years which agrees with data from modern societies lacking medical care (Mays, 2007). In addition to this 15% of burials were infants (aged under one year).
Stature provides information on any physiological stress which occurred during development due to nutrition or disease (Mays, 2007a). Low childhood stature suggests disease and poor nutrition was present in the population. When compared to data from 19th century urban factory working children the Wharram Percy children were not taller suggesting nutrition was the same as it was for the urban poor (Mays, 2007a). The average stature for adults in the Wharram Percy collection was 168.8cm for males and 157.8cm for females. This is similar to St Helen-on-the-Walls, a churchyard which served a poor parish in York, and is similar to other late medieval sites (Mays, 2007a).

4.2.2.2. Sample analysed from the collection

From the Wharram Percy collection a total of 181 individuals were selected for analysis based on the exclusion criteria below. A final number of 111 individuals were analysed due to post-mortem damage on both femora of 70 individuals. From the final 111 individuals, due to post-mortem damage or only one femur being present, it was only possible to measure alpha angles and/or non-metric traits on 99 left and 99 right femora. In some cases, of these 198 femora, post-mortem damage to the distal aspect of the femur or the greater trochanter meant it was not possible to measure alpha angles however it was still possible to record non-metric traits. In other cases, it may not have been possible to record the non-metric traits but alpha angles could still be measured. The number of femora included for each section of analysis will be included throughout the result section.

Exclusion criteria included:

- Any individual with an estimated age-at-death of <18 years/ unfused femoral epiphysis
- No femora, acetabula or pubic symphysis present
- High levels of post-mortem damage to the femur which would affect recording
- Those with restricted access by the museum or difficulty with access
- DISH or ankylosing spondylitis (characterised by sacroiliac joint fusion and fusion of the ligaments, candle-wax appearance on the right side of at least four vertebrae (Resnick and Niwayama, 1976; Ortner, 2003; Saleem and Hawass, 2014) as it has been reported in the literature to present at the hip joint in a similar way as FAI (Tannast et al., 2007; Anderson et al., 2010).

The age and sex estimations originally carried out by the curators, as outlined in (Mays, 2007a), was provided during the data collection process and used in this study. An additional sex estimation was performed during the analysis, using Buikstra et al. (1994) however due to the level of agreement, the findings reported by the curators was used with regards to age and sex. Both males and females were selected for analysis to determine if there is any sexual dimorphism in any of the recorded changes. The distribution within the sample based on age and sex is presented in Table 4-2 below.

Table 4-2 Distribution of the Wharram Percy sample by age range categories and sex

	Age range categories				
Sex	18-29	30-49	50+	Indeterminate	Total
Males	12	21	21	14	68
Females	12	19	8	1	40
Female?	1	2	0	0	3
Total	25	42	29	15	111

The number of individuals from each excavation area included in this study are presented in Table 4-3 below. Individuals were not excluded based on phase from this study due to the requirement for increased sample size. This sample therefore represents a time span from the 10^{th}-19^{th} century which needs to be considered when analysing the impact of physical activity. It cannot be assumed the level and type of physical activity did not vary over such a broad time period with changes in technology and land use, as discussed in section 4.2.2.1. In their initial analysis of the skeletal collection from Wharram Percy, Mays (2007a) did not find "evidence for any great secular change in post-cranial skeletal morphology" therefore although it is likely there would have been a change in activity, the osseous markers analysed by Mays do not reflect this significantly. This population were still an agricultural and continuously involved in physically demanding manual labour in comparison to a modern urban population but this caveat needs to be recognised when interpreting results.

Table 4-3 Number of individuals per excavation area from the Wharram Percy collection

Excavation areas	N of Males	N of Females	N of Female?	Total N
G	13	11	0	24
NA	14	6	2	22
CN	12	5	0	17
WCO	15	10	1	26
SA	5	3	0	8
V	3	1	0	4
EE	6	4	0	10

4.2.3. Luís Lopes Identified Skeletal Collection (LLC)

The Luís Lopes or Lisbon Collection (LLC) is housed at the Bocage Museum (National Museum of Natural History), Lisbon, Portugal. A brief history of the collection was published by Cardoso (2006). The collection was initiated by Luís Lopes from 1981-1991, then Hugo Cardoso from 2000. At the time of Cardoso (2006) the collection consisted of 1,692 skeletons, however the collection continues to be curated. Six hundred and ninety nine skeletons have basic documented information readily available from coffin plates, grave numbers, cemetery registers and death registration records, which includes: age at death, place of birth, occupation, date and cause of death (Cardoso, 2006). The collection consists predominantly of those of Portuguese nationality, with 45% of which coming from the district of Lisbon. In addition to this there are individuals from former Portuguese overseas colonies and individuals from Brazil, Spain, France and Italy (Cardoso, 2006). The years of death are between 1880 and 1975, with the age at death ranging from 0 to 98 years, however largely consisting of those over the age of 50 years (Cardoso, 2006). In terms of socio-economic status, it was determined this collection represents a low to middle socioeconomic strata based information on known male occupation (Cardoso, 2006).

Identified skeletal collections are valuable for bioarchaeological study due to the quantity and quality of the data available regarding each individual. Unlike the use of archaeological collections, were age estimates are purely biological ages, based on observable osseous changes in sometimes wide and inconsistent brackets, identified collections provide accurate age information. Identified collections have been used to test and develop methods of age and sex estimates, as well as determine associations between osseous changes and disease or activity (Alves Cardoso and Henderson, 2013; Matos and Santos, 2006;Cardoso and Henderson, 2010; Campanacho et al., 2012). The LLC was therefore included in this study for several reasons. The availability of occupational information made it possible to address the research aim of determining if there is a link between cam morphology and occupational activity. While the exact age data for each individual made it possible to control for this factor when analysing the presence of osteitis pubis and cam morphology. This collection also represents a late 19th- early 20th century urban population which contrasts to the medieval rural population of the Wharram Percy collection. This therefore allowed comparisons between collections to determine if there was a difference in non-metric traits and cam morphology between the rural and urban settings.

4.2.3.1. Contextual Information

Lisbon is the capital city of Portugal, located in the south centre of the country. The city covers over 84km^2 and extends along the Tagus River for 18.8km. It is a hilly city with the altitude ranging from 6 to 226m (Oliveira and Pinho, 2010).

The collection consists of individuals who lived during the 1800s and 1900s. During this time Portugal went through many political changes which had an impact on the sociocultural environment of the country. The 19th Century saw a period of political instability and civil unrest. During this period the fight for power by political forces lead to various coups, dictatorship and periods of civil war in the country (Baiôa and Fernandes, 2003).

Portugal was a declining world political power by the end of the 19th century. The agricultural system was fragmented, and industrialisation was late (Cardoso, 2007). It was not until the 1970s, following the dictatorship being overthrown that there were improvements to social welfare of the country (Cardoso and Garcia, 2009). The late 19th and early 20th century saw migration towards the urban centres from agricultural settlements causing huge population growth in Lisbon (Cardoso and Garcia, 2009). The economy in Lisbon was mixed. A combination of manufacturing and service sector, as well as, to a lesser extent agriculture and fishing. In the late 18th century around half the male work force was around trade, transport, public service and liberal professions while one third was made up of craftsmen and apprentices (Reis, 2009). From the 1840s industrialisation took place and around 1900 employment in industrial related trades, such as construction, made up 40% of the work force and the service sector was approximately 35% (Reis, 2009). This society has been reported to have had low social mobility with many fathers and sons had the same/similar occupations (Reis, 2009).

Like many other large cities at the time the descriptions of the living conditions during this time were particularly negative, being described by novelists as “sombre and fetid” (Reis, 2009). The increase in population density, due to industrialisation, caused overcrowded unsanitary living conditions for the working classes. To illustrate this, Moreira (1950) as cited in Cardoso and Garcia (2009), found 43% of working-class housing had no piped water, 69% had no electricity and 81% had no toilet. In the early 20th century health care was fee-paying and restricted. The Portuguese National Health Service was then introduced between 1974 and 1981 (Veiga et al., 2000). The introduction of these services can be seen to have had direct effects on the health indicators of the population such as mortality rates. Between 1950/55 and 1990/95 there was an increase in life expectancy of 13.9 years for men and 16.2 years for women (Veiga et al., 2000).

4.2.3.2. Sample analysed from the collection

A total of 172 male skeletons were selected for this study, however a total of 108 males were recorded due to the presence of post-mortem damage, DISH or access issues. From the final 108 individuals, due to post-mortem damage or only one femur being present, it was only possible to measure alpha angles and/or non-metric traits on 106 left and 106 right femora. In some cases, of these 212 femora, post-mortem damage to the distal aspect of the femur or the greater trochanter meant it was not possible to measure alpha angles however it was still possible to record non-metric traits. In other cases, it may not have been possible to record the non-metric traits but alpha angles could still be measured. The number of femora included for each section of analysis will be included throughout the result section. Exclusion criteria were the same as for the Wharram Percy collection with the addition of:

- Conditions recorded as cause of death known to have a potential impact on the pubic bones e.g. urinary tract infection (LLC only).
- Females
- No occupation information available

Only males were included in this sample due to the ambiguous nature of the recorded occupational information for females. Eighty five percent of the females in the collection had an occupation recorded as 'housewife' (Cardoso, 2006). It is too difficult to determine the nature of the work these women would have undertaken and how physically demanding this would have been therefore they were excluded from this sample.

The average age for the selected sample is 53.8 years and with a range of 69.0 years. Figure 4-2 shows the sample distribution for age-at death for the study sample.

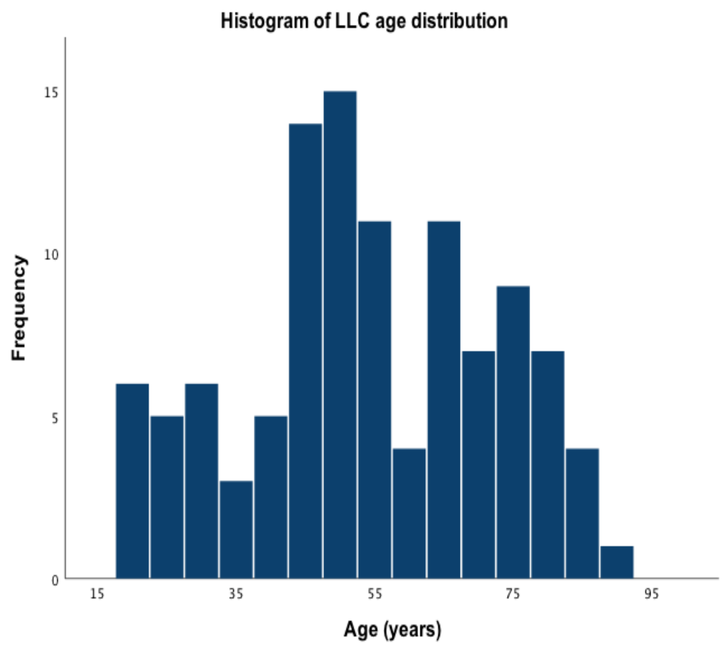


Figure 4-2 Histogram of LLC sample age (years) data

4.2.3.3. LLC occupational activity categories

The total list of occupations from the LLC was grouped into occupation categories using the International Standard Classification of Occupations 2008 (ISCO-08) publication and database (International Labour Office (ILO), 2012). The ISCO-08 was developed as a system for the classification of occupational information to allow global comparison. It classifies all jobs in the world into 436 groups, which are further grouped into 130 minor groups, 43 subgroups and 10 major groups. These groups are based on skill level and specialisation required for each job, with information being obtained via statistical censuses and surveys. For each of the 436 groups of occupations a list of job-specific tasks is also provided. The 10 major groups include:

0. Armed Forces Occupations
1. Managers
2. Professionals
3. Technicians and Associate Professionals
4. Clerical Support Workers
5. Services and Sales Workers
6. Skilled Agricultural, Forestry and Fishery Workers
7. Craft and Related Trades Workers
8. Plant and Machine Operators and Assemblers
9. Elementary Occupations

This system has been employed here as it proves a global list of occupations and therefore not specific/bias to one country. Furthermore, it provides a detailed description of the job-specific tasks for each occupation listed, which is useful for further categorisation in to occupational activity groups.

Each of the occupations from the LLC were identified in the ISCO-08 database and grouped into one of the major groups. Some occupations documented for the LLC had a level of ambiguity, for example, ‘hospital employee’; which could be any combination of occupations and therefore would fall into several ISCO-08 categories from 1 to 9. An additional group, ‘10. Undetermined’, has therefore been created for those occupations too ambiguous to categories in this manner. To further sort these categories to allow statistical analysis, Major Groups ‘1. Managers’ and ‘2.

Professionals' were combined to form 'Group 1. Managers/Professionals'. Group 6 was also removed due to no individuals having occupations applicable to this category. Group '8. Plant and Machine Operators and Assemblers' was also removed and the two individuals placed under this category were added to Group '4 Services and Sales Workers' as it was felt the occupation of "Driver" was relevant for this category. This formed the categories as shown in Table 4-4 for occupations within the sample.

Table 4-4 Number of individuals per updated ISCO-08 categories

Occupation Groups	N	%
0. Armed Forces Occupations	8	7.4
1. Managers/Professionals	10	9.3
2. Technicians and Associate Professionals	7	6.5
3. Clerical Support Workers	12	11.1
4. Services and Sales Workers	20	18.5
5. Craft and Related Trades Workers	35	32.4
6. Elementary Occupations	4	3.7
7. Undetermined	12	11.1
Total	108	100.0

The occupations for the LLC were grouped to explore the association between non-metric traits and/or alpha angles with physical activity. Various anthropological studies have utilised identified skeletal collections to determine the affect physical activity has on various parameters on the skeleton e.g. Campanacho et al., 2012; Cardoso and Henderson, 2010; Niinimäki and Baiges Sotos, 2013; Zampetti et al., 2016. These collections allow an opportunity to further understand the occupations of past populations, as well as, activity related skeletal changes (Perréard Lopreno et al., 2012). Throughout the many studies utilising identified skeletal collections there are various methods used to categorise occupational groups. The article by Perréard Lopreno et al. (2012) provides an overview of the various methods used to categorise activity from documented occupational information using identified skeletal collections. The sheer number of methods used highlights just one of several limitations in doing so. In addition, the differences in methods used to categorise occupations makes comparisons between studies difficult. The use of documented occupation information is not without its pitfalls as outlined below (highlighted by Alves Cardoso and Henderson (2013):

- A record of occupation does not provide full information on all activities an individual was involved in, for instance, it would not be possible to determine recreational activities.
- The occupations recorded only presents occupation at one time point, not allowing for changes at different points in life.
- If incomplete or unclear documentation is provided, this could affect interpretation.
- There are difficulties in determining the physical aspects and tasks the occupations require.
- Other stimuli from the individual's environment can also play a large role in this e.g. age, socio-cultural environment, recreational activities or duration spent in the listed occupation and previous occupations.
- Difference in perspectives on the interpretation of occupations due to social, cultural and economic setting in which they are interpreted.

While some of these factors are unavoidable, such as; the lack of awareness regarding recreational activity, the methods used in this study attempted to overcome several of these factors. Although there is a possibility of a change in occupation during an individual's life the low social mobility at this time in Portugal meant it was possible to assume the last occupation was an accurate representation of the level of occupational physical activity during the individuals life (Campanacho et al., 2012). An international classification system was used to remove the difference in perspective with regards to interpretations of occupations between different cultures. Other factors such as, age and sex, are controlled for during the analysis to prevent any possible effect they may have and in the discussion chapter various other stimuli will be addressed.

Three different methods of activity classification have been incorporated in this study to remove the possibility that the method used will impact the results. Alves Cardoso and Henderson (2013) found the frequency of recorded entheseal changes was dependent on the method used to categorise occupational activity. They found this to impact significance and therefore the interpretation of the results. It was felt the inclusion of several methods was important to determine if there was a difference in results and interpretation dependent on the classification methods used. Methods I & II, used modern international occupation classification systems and a comprehensive database of energy expenditures for certain activities to classify physical activity (described in more detail below). Methods I & II were included as they provided a quantitative method for categorising occupations and therefore reduce user subjectivity when categorising each occupation. While method III used a reference database of compiled occupational categories from previous identified skeletal collection studies. This method was included to provide comparable data to other studies analysing identified skeletal collections. Additionally, the energy expenditure values used in the previous methods have not been widely used in bioarchaeological study and therefore it was felt it was important to include a previously tested method.

Methods I & II: ISCO-08 and compendium of physical activity

Deyaert et al. (2017) devised a method to determine the level of physical activity for various occupations, by combining a database of the energy cost of specific activities (the Compendium of Physical Activities) and the international classification system (ISCO-08). This method was formulated to overcome the limitations of using self-reported methods, such as issues with recall and social bias, and wearable devices such as small sample sizes and lack of context (Deyaert et al., 2017). This method applied Ainsworth and colleagues' 'Compendium of Physical Activities', as a resource to classify the energy cost of particular activities (Ainsworth et al., 2011). The Compendium provides a list of daily physical activities and an associated measure of physical activity energy expenditure in the form of Metabolic Equivalent of Task (MET) values. The MET values are defined as "the ratio of the work metabolic rate to a standard resting metabolic rate of 1 kcal/kg/h" and therefore indicate how physically demanding an activity is compared to a situation at rest (Ainsworth et al., 2011). The activities found in the Compendium and the associated MET levels were obtained from various sources including surveys, logs, dairies and charts, tables and published studies respectively (Tudor-Locke et al., 2009). The compendium has been used in bioarchaeological study by Winburn and Stock, (2019) and Winburn (2019). In their study, Deyaert et al. (2017) attached MET values from the Compendium to each job-specific task listed for each of the 436 occupations from the ISCO-08 manual. A MET value for each occupation was calculated by averaging the job-specific MET values for each occupation. This method allowed MET values to be applied for every occupation in the ISCO-08 manual.

The method created by Deyaert et al. (2017) has been implemented in this study to allow the groupings of occupations based on level of physical activity. Each of the LLC occupations were located in the ISCO-08 manual and database which allowed a list of tasks for each occupation, based on information from ISCO-08, to be collated. Those tasks which were unlikely to have been performed in 19^{th}-20^{th} century were excluded e.g. computer work. Using the database compiled by Deyaert et al. (2017) of MET values for each individual task and the average for each occupation, the adjusted average was applied to each occupation from the LLC.

Several of the occupations were difficult to assign to a specific occupation in the ISCO-08, including:

- City Council Employee
- Hospital Employee
- Student
- Civil Servant
- Corporation employee
- Industrial

These occupations were therefore excluded to avoid bias, as they could not be linked to various occupations in the ISCO-08 list. In addition to this, ‘armed forces occupations’ did not have a list of tasks in the ISCO-08 manual. Deyaert et al. (2017) assigned an average MET score of 2.5 for those occupations without clear tasks, however, as there is an array of job roles within this occupation category it is difficult to determine the true MET score. The armed forces occupations were therefore excluded from this section of analysis.

Once the average MET score had been calculated for each occupation, in addition to using this data in a continuous manner, the list was divided into groups based on physical activity levels. The determination of groupings for occupational activity was done in two ways:

Method I: Percentiles within the sample

The first method used to categorise physical activity was achieved by dividing the sample MET values into percentiles:

- Low physical activity (33rd Percentile): ≤ 2.22222
- Moderate physical activity: > 2.222 < 3.0000
- High physical activity (67th Percentile): ≥ 3.000

This method was included to analyse the impact of different levels of physical activity within the sample. Low physical activity represents the lowest 3rd of occupation MET values while the high physical activity category is the highest 3rd of MET values within this sample.

Method II: Ainsworth et al. 2011 intervals for determining physical activity

In their article Ainsworth et al. (2011) list the commonly used activity thresholds for determining the level of physical activity based on MET values, from various studies (Pate, 1995; Pate et al., 2008; Tudor-Locke et al., 2009; Patel et al., 2010). These intervals have been used here to divide the population into groups based on physical activity and include:

- Sedentary behaviour (1.0-1.5 METs)
- Light-intensity (1.6-2.9 METs)
- Moderate-intensity (3-5.9 METs)
- Vigorous intensity (≥6 METs)

These categorise were included as they are commonly used, predefined threshold values determined through various previous studies. These thresholds have been tested and determined to represent each of the levels of physical activity they have been allocated too. Additionally, the inclusion of widely used thresholds allows the production of comparable data.

Method III: Bioarchaeological classification

Perréard Lopreno et al. (2012) addressed various methods of classifying occupations from identified skeletal collections by physical activity and thus a reference database was formed to allow a level of comparison between future studies. In their study they included eight case studies, from seven identified skeletal collections in Europe. They showed typically two forms of classifying criteria, biomechanical and socio-cultural criteria, were used to categorise occupations. They found a high level of agreement between studies using biomechanical criteria, while the socio-cultural categorisation methods were not as comparable. The categories of manual and non-manual activities showed low discrepancy between authors and, in the database, there were more occupations categorised using this method than for other biomechanical criteria. For these reasons, occupations were grouped in this way. To achieve this, occupations were located within the database and grouped, as listed, as either:

- Manual
- Non-manual
- Undetermined (if the occupation was not listed in the database)

This method was used to allow the creation of comparable data to other studies on occupational activity using identified skeletal collections. It was also included to determine if there was a difference between methods generated for identified skeletal collections and methods from modern living population information (MET values). Furthermore, this method does not rely on MET values which have not been commonly used for bioarchaeological study, and so it is undetermined if they are applicable to past populations.

4.3. Methods

This section describes the methodology used to analyse both the skeletal collections and the 3D volume rendered CT models. It also outlines the statistical analysis used and the inter- and intra-observer error rates.

4.3.1. Photography

For both skeletal collections, to determine the presence of cam morphology measurements were recorded on digital photographs to replicate clinical measurements, without the use of medical imaging. The only method developed for these measurements is by Toogood et al. (2009). This method was selected as it does not require the bones to be held in a way that could potentially cause damage, it is currently the only method that replicates the medical imaging orientation commonly used to record alpha angles, it is simple to reproduce and the results are comparable to previous studies incorporating the same method (Moats et al. 2015; Fikkers et al., 2015; Lawrence et al. 2018; Unnanuntana et al., 2010).

Figure 4-3 Photography set up at Bocage Museum, Lisbon

The images were taken with the camera set up perpendicular to the desk (axial view). A fixed arm was used to ensure the camera was held in this position throughout the recording (as shown in Figure 4-3), allowing each image to be in the same orientation. Adapted miniature spirit levels were attached to the camera to ensure it was levelled at all times. 'Inclination view' photographs were taken from this orientation. For the inclination view, the femur was rested on the desk, ensuring both medial and lateral condyles and the greater trochanter were in contact with the desk surface. The femur was abducted, so the femoral neck was parallel to the edge of the table. The inclination view is thought to mirror the MRI slice used by Nötzli et al. (2002) to measure alpha angles (Moats et al., 2015). Additional photographs were taken of the pubic symphyses and the anterior aspect of the femoral head-neck junction.

4.3.2. CT 3D volume rendering

All CT scans were input into Horos, in the form of DICOMs, to create the 3D volume rendered models. Horos is a free and open source code software (FOSS) program that is distributed free of charge under the LGPL license at Horosproject.org and sponsored by Nimble Co LLC d/b/a Purview in Annapolis, MD USA.

To produce the 3D volume rendered models of each femur, regions of interest (ROI) were set via HU (Hounsfield units) threshold values. The Hounsfield scale represents the density of the tissue being scanned. Water has the density of 0 HU while air has a value of -1000 HU. This unit of measure, therefore, allows the differentiation of different tissues due to the difference in density (Broder, 2011). This was achieved using the 'Grow Region (2D/3D segmentation)' option. Once in this option, by selecting the area of interest, the ROI is defined by HU thresholds. This option allows ROI to be applied to each slice based on this initial selection. Through manual inspection all other selected bones were erased to leave only the femora as the ROI. To exclude the areas outside the selected ROI, the pixel values were set to -3024 (the default number for black), to exclude them from the final rendering. The 3D volume rendering setting was then selected to produce the model.

To orientate each femur to be in a comparable manner to the inclination photography view, the axial view orientation setting was selected, which orientated the bone on its posterior surface (pointing down) with the inferior aspect orientated towards the screen. The model was then rotated to view the superior surface, ensuring both trochanters were inline. The model was then rotated either medially or laterally (abduction or adduction of the femur), dependent on side, to achieve maximum exposure of the femoral neck. No smoothing was used to avoid loss of any osseous changes.

4.3.3. Quantitative measurements

Alpha angle measurements are the most commonly used method to determine the presence of cam morphology clinically. For this reason, this quantitative measurement has been included in this study. Offset ratio measurements were also included as several studies (e.g. Toogood et al., 2009; Fikkers et al., 2015; Zeng et al., 2016) have shown a relationship between this measurement and alpha angle size. For each of these studies, using the offset ratio method as outlined by Toogood et al. (2009), with increasing alpha angles comes smaller anterior/posterior offset ratios and therefore a more posteriorly offset femoral head. It was felt that it was important to include this measurement in the study of cam morphology as it clearly has an impact. Additionally, due to the differing locations along the head and neck region of the non-metric traits included in this study the orientation of the femoral head in relation to the neck is likely to have an impact on the alpha angle size due to these traits. For instance, if the trait is located on the junction between the head and neck, with a more posteriorly orientated head this would cause a higher alpha angle than if the head was more anterior translated with the same trait. Offset ratios were therefore measured to be controlled for when analysing the presence of cam morphology both individually and in relation to non-metric traits.

4.3.3.1. Alpha angle measurements

All measurements were made using Fiji (a form of ImageJ software) (Schindelin et al., 2012). To measure the alpha angles, as shown in Figure 4-4, the centres of the femoral head and neck were identified. To achieve this, a best fit circle was drawn around the femoral head and the centre of the circle was found automatically. To identify the centre of the femoral neck the rectangle tool was used. The four points of the rectangle were placed, two points on either side, at the narrowest points of the neck. The centre of the rectangle is found automatically. A line was then drawn through the centre of the femoral neck to the centre of the femoral head. Then a line from the centre of the femoral head to the point where the surface of the neck intersects with the circle around the femoral head anteriorly. For this study, alpha angle cut-off values of ≥50˚, ≥55˚ and ≥60˚ were used to indicate the presence of cam morphology. These thresholds were used as they were the most commonly utilised in the literature.

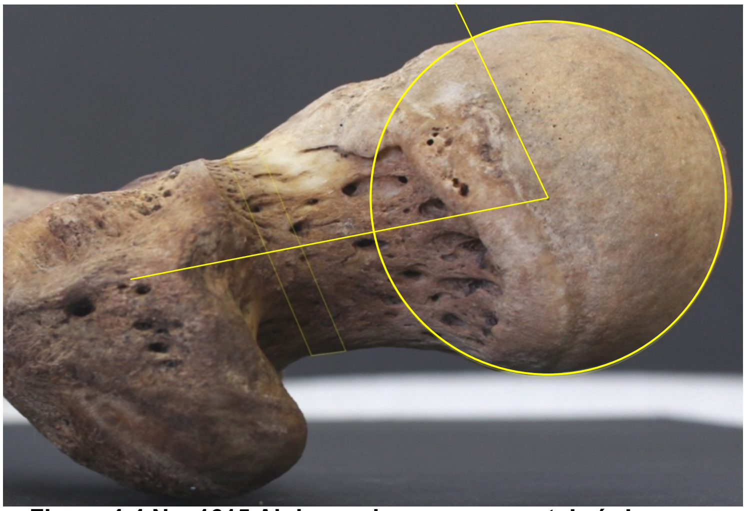


Figure 4-4 No. 1615 Alpha angle measurement. Luís Lopes Anthropological Collection, MUHNAC (Photograph by E. Saunders © ULisboa-MUHNAC)

4.3.3.2. Offset ratio measurements

The method to measure offset ratios was also as per Toogood et al. (2009) and using Fiji. On the inclination view images, the centre axis of the femoral neck (irrespective of the femoral head) was found by placing three parallel lines, each directed from the anterior side of the neck to the posterior side, at the narrowest points. Fiji automatically placed markers at the centre of each of these lines. A line was placed along each of these central points, which produced the central axis of the neck. Two lines, parallel to the central axis line are drawn, with one against the concavity of the femoral neck and one by the convexity of the femoral head. The anterior (AOS) and posterior (POS) offset are the differences between these two lines, on the anterior and posterior side of the femoral head-neck region. Offset ratio is the calculated as AOS/POS. In this study the height measurement of the rectangular tool was used to determine AOS and POS to ensure these lines were parallel. Figure 4-5 is an example of how the offset ratio measurements are taken.

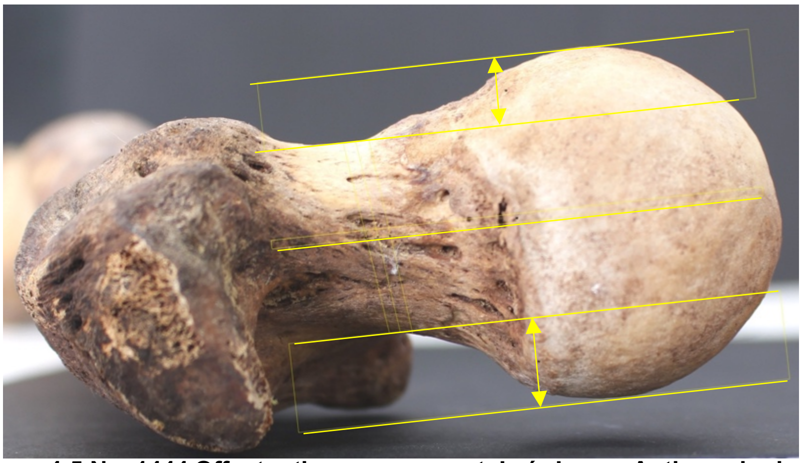


Figure 4-5 No. 1444 Offset ratio measurement. Luís Lopes Anthropological Collection, MUHNAC. (Photograph by E. Saunders © ULisboa-MUHNAC)

4.3.4. Non-metric trait recording

Non-metric traits of the anterior-aspect of the femur were recorded using the method by Radi et al. (2013). These traits included; Poirier's facets, plaque and cribra. This method was selected as it allows a more consistent approach to the identification and recording of non-metric traits on the anterior aspect of the femur in comparison to other methods. Table 4-5 below is the recording criteria produced by Radi et al. (2013) for each non-metric trait. Figures 4-6 to 4-11 are images taken during this study demonstrating examples of each of these traits.

Figure 4-6 No. 373 Poirier's Facet. Luís Lopes Anthropological Collection, MUHNAC. (Photograph by E. Saunders © ULisboa-MUHNAC)

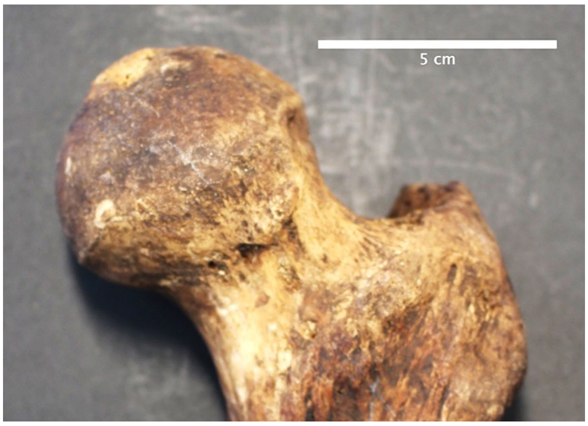


Figure 4-7 No. 233 Plaque, Type A. Luís Lopes Anthropological Collection, MUHNAC. (Photograph by E. Saunders © ULisboa-MUHNAC)

Figure 4-8 No. 236 Plaque, Type B. Luís Lopes Anthropological Collection, MUHNAC. (Photograph by E. Saunders © ULisboa-MUHNAC)

Figure 4-9 No. 1226 Plaque, Type C. Luís Lopes Anthropological Collection, MUHNAC. (Photograph by E. Saunders © ULisboa-MUHNAC)

Figure 4-10 No. 391 Cribra, Type 1. Luís Lopes Anthropological Collection, MUHNAC. (Photograph by E. Saunders © ULisboa-MUHNAC)

Figure 4-11 No. NA094 Cribra, Type 2. Wharram Percy Skeletal collection, Historic England. (Photograph by E. Saunders)

Table 4-5 Non-metric traits classification method by Radi et al. (2013)

Feature	Definition	Recording method
Poirier's facet	Lateral expansion of the anterior portion of the femoral head articular surface towards the anterior aspect of the femoral neck. Expansion surface is virtually smooth, on the same plane and in continuity with the articular surface of the head.	0. Absent 1. Present NR. Not recordable
Plaque	Imprint located on the anterior margin of the femoral neck close to the head. The plaque may be present in three shapes (form) and mat be delimitated, even partly, by a distinct border (edge).	0. Absent 1. Present NR. Not recordable Form: A. The plaque is on the same plane as the femoral head, but is perceptible as a distinct formation, due to its entirely rough surface, with respect to the head surface, which is smooth B. The plaque is on an intermediate plane between the femoral head surface and the neck surface C. The plaque surface is entirely or in part lower than the femoral neck plane NR. Not recordable Edge: 0. Absent 1. Bony rim protruding no more than 1mm 2. Pronounced bony rim protruding more than 1mm NR. Not recordable
Cribra	Cortical discontinuity in a circumscribed area on the anterior portion of the femoral neck, next to the head. Any porosity on the articular surface of the femoral head as well as on the physeal scar is not to be taken in account	0. Absent 1. Clustered pores (diameter ~2mm or more) on cortical surface 2. Cortical erosion with exposition of trabeculae. Area of erosion could be depressed NR. Not recordable

4.3.5. Osteitis pubis recording

Osteitis pubis recording criteria was developed through a review of the clinical literature. Articles which included descriptions of osseous changes at the pubic symphysis for symptomatic individuals with osteitis pubis were included, while those which presented; single case reviews only, bacterial osteitis pubis and cases due to parturition, were excluded. The most common diagnostic observations for osteitis pubis at the pubic symphysis from the literature included; sclerosis, widening, vertical displacement, subchondral cysts, osteophytes, erosions and irregularity (See appendices 1 for examples of the articles included). A major limitation of using clinical radiographic observations to determine criteria visible on osseous specimens has previously been highlighted (Mays, 2012). When forming these recording criteria those changes which could not be observable on skeletal remains were excluded including; widening and vertical displacement. Porosity and eburnation on bone has been reported to correspond to subchondral cysts and sclerosis seen on radiographs in the living (Mays, 2012). The porosity usually corresponds to subchondral cysts and eburnated bone is sclerotic (Mays, 2012; Rogers and Waldron, 1995; Rogers et al., 1990). The observed features from previous literature, suggesting the presence of osteitis pubis on skeletal remains, were also considered when forming these criteria.

The resulting criteria much resembles that used for the recording of osteoarthritis at other areas of the body. The pubic symphysis is capable of a small amount of movement (Becker et al., 2010) and some of the main reported imaging criteria included widening and vertical displacement of the symphysis which are indicative of movement (Miller et al., 2003). In addition to this, Calce et al. (2017) included osteitis pubis in their analysis of osteoarthritis. The recording criteria shown in Table 4-6 was applied to each pubic symphysis from both skeletal collections. Each feature was recorded as absent (A), present (P) or unobservable (U). Figure 4-12 to 4-16 show example of pubic symphysis recorded for having each of the recording criteria, 4-12 demonstrates eburnation focused predominantly at the rim, 4-13 shows porosity to the symphysial face, 4-14 demonstrates erosions, 4-14 shows irregularity and 4-15 demonstrates osteophytes.

Table 4-6 Osteitis pubis recording criteria

Feature	Description
Eburnation	Smooth, polished appearance of exposed subchondral bone caused by bone-on-bone contact at articular surfaces (Buikstra et al., 1994)
Porosity	Small openings that pass directly or indirectly through a structure (Buikstra et al., 1994)
Erosions	Areas of bone loss, often at the joint margins or, in some cases, on the joint surface. True erosion has the following characteristics: Cortical destructions, undercut edges, exposed trabeculae, sharp or scalloped ridges, scooped floor (Waldron, 2012)
Irregularity	Articular surface irregularity
Osteophytes	Small abnormal bony outgrowth or protuberance (Buikstra et al., 1994)

Figure 4-12 No. 465 Eburnation. Luís Lopes Anthropological Collection, MUHNAC. (Photograph by E. Saunders © ULisboa-MUHNAC)

Figure 4-13 No. NA066 Porosity, Wharram Percy Collection, Historic England. (Photograph by E.Saunders)

Figure 4-14 No. EE099 Erosions. Wharram Percy Collection, Historic England (Photograph by E. Saunders)

Figure 4-15 No. WCO109 Irregularity, Wharram Percy Collection, Historic England. (Photograph by E. Saunders)

Figure 4-16 No. EE099 Osteophytes, Wharram Percy Collection, Historic England (Photograph by E. Saunders)

4.3.6. Statistical analysis

The current section describes the statistical methods performed throughout this study. All statistical analysis was performed using SPSS 25.0 for Mac. Unless stated otherwise, the results will be present in the formation of mean ± standard deviation. A significant difference was determined by a p-value of <0.05, unless a Bonferroni correction is applied (this will be stated in the text).

Unless carrying out paired analysis, the left and right femur were analysed separately. This was to ensure the assumption on independence was met as it cannot be assumed variation on one side is independent of the other.

Where possible descriptive statistics were reported for each continuous variable, these include; frequencies and percentages, as well as mean, minimum, maximum, range and standard deviation. All continuous variables were tested for normal distribution using the Shapiro-Wilk statistical test to determine if parametric tests could be used. Normality was assumed when $p > 0.05$ for Shapiro-Wilks test. If $p < 0.05$ the normality Q-Q plots were inspected. When the sample size was >30, normality was assumed in accordance with the central limit theorem (Weiss, 2017). If data was not normally distributed a comparison test, with transformed data, was run to determine if the violation of the assumption of normality impacted the results (Osborne, 2011). If there was no difference in significance then the untransformed data was used. If it was not possible to transform the data a non-parametric comparison test was included. Any outliers present in the data were assessed to determine if they were extreme. If an extreme outlier was present (considered as data points ±3 standard deviations from the mean) a comparison test was run excluding the outlier, to determine if its presence had an impact on the results (Osborne and Overbay, 2011). If the conclusions of the comparison test differed from the original test, the results of each test have been presented.

Pairwise comparison was performed using paired sample t-tests for continuous variables, while a McNemar's test was used for categorical variables. Only individuals with both observable femora were included in these tests.

Independent-sample t-tests were run to determine if there was a significant difference between the means of two independent groups on a continuous dependent variable. The assumption of homogeneity of variances was assessed using a Levene's test for equality of variances. When violated ($p < 0.05$), a Welch's t-test was used. If the assumption of normality was violated and the data could not be transformed to meet this assumption a non-parametric Mann-Whitney U test was used (Field, 2013). When there were more than two independent groups, a one-way ANOVA was included. If a significant difference was determined a Tukey post hoc analysis was performed. If homogeneity of variances were not met a Welch ANOVA was run with a Games-Howell post hoc test if a significant difference was identified. If the data was not normally distributed and it was not possible to transform the data a Kruskal-Wallis H test was used (Field, 2013). Two-way ANOVAs were run to determine if there was interaction effect between two independent categorical variables on a continuous variable. If there was a significant interaction a simple main effects was run (to determine the effect of one variable at individual levels of the other variable) while if there was not a significant interaction a main effects analysis was run (To determine the variance accounted for by each independent variable) (Field, 2013). One-way ANCOVAs were performed in order to determine if there was a significant difference between adjusted means between nominal variables (Field, 2013).

To determine if there were differences in the proportions of categorical variables were significantly different the chi-squared tests of homogeneity or fisher's exact tests (if expected count <5) was run (Field, 2013).

Correlations between variables were determined through the use of Spearman's and Pearson's tests. The Spearman's test was run when the assumption of normality was not met.

In order to establish if it is possible to predict the probability a femur would be categorised as having Poirier's facets and also to predict the probability a femur would have cam morphology present based on the presence of non-metric traits, binary logistic regression was run. An outlier was present if any case had a standardized residual with a value greater than ±3 standard deviations. In each case this was inspected however if there was no reason to exclude the case they remained in the analysis. Another assumption of this test is linearity of the continuous variable with respect to the logit of the dependent variable. This was assessed by the Box-Tidwell procedure ($p > 0.05$).

4.3.7. Intra and Interobserver error measurements

Alpha angle measurements

A random sample of 20 femora was generated using a random number generator for the Wharram Percy collection and 20 for the Luís Lopes collection. Alpha angle measurements were repeated by the lead researcher several weeks following the original measurements being taken. The same random sample of 40 femora (20 from each collection) was also measured by a separate scorer (P.Z.) following instructions provided by the lead researcher. The separate scorer had no previous experience taking these measurements. Both the lead researcher and the separate scorer were unaware of the previous measurements. Intra- and inter- observer error rates were determined using intraclass correlation coefficients, with values of >0.65 denoting good correlation and values of >0.75 denoting excellent correlation. Table 4-7 includes the intra- and inter- observer error rates for both the Wharram Percy and Luís Lopes collections.

Table 4-7 Alpha angle, intra- and inter- observer error rates for both skeletal collections

Collection	Intraobserver	Interobserver
Wharram Percy	0.934	0.946
Luís Lopes	0.983	0.720

Non-metric traits analysis

For non-metric trait error rate analysis, only data from the Wharram Percy collection was used as it was not possible to perform this analysis on the Luís Lopes collection data due to time and resource limitations. However, as the same method has been used on both collections the results from the Wharram Percy collection can be regarded as a good representative of the repeatability of this method.

A random sample of 25 skeletal remains from the Wharram Percy collection were selected using a random number generator. It was not possible to record one individual due to pathological changes therefore leaving a total of 24 recorded. Both left and right side were recorded for each individual. Any femora recorded as unobservable was also excluded leaving a total of 43 femora. For intraobserver error rates the lead researcher recorded the presence of non-metric traits with the same scoring system several months following the original analysis. For the Interobserver error rates a separate scorer (NMG), using the method outlined and scoring sheet for the original analysis, also scored each femur for non-metric traits. Both the lead researcher and separate scorer were unaware of the original results at the time of analysis. The separate scorer did not have any prior experience with this method. A Cohen’s kappa analysis was run to determine if there was agreement between the original data and the separate scorers results to determine interobserver error rates. While the intraobserver error rates were determined also using a Cohen’s kappa analysis to compare the original data to the second scoring session by the lead author. The strength of agreement based on the value of Cohen’s kappa coefficient include; <0.20 as poor agreement, 0.21-0.40 as fair agreement, 0.41-0.60 as moderate agreement, 0.61-0.80 as good agreement and 0.81-1.00 as very good agreement (Altman, 1991). The results of the intra- and inter- observer error rates for the non-metric trait analysis is shown in Table 4-8 below

Table 4-8 Non-metric trait intra- and inter- observer error rate measurements, Wharram Percy collection

Non-metric trait	Intraobserver	Interobserver
Poirier’s facets	0.728	0.488
Plaque (absent or present)	0.668	0.619
Plaque (by type)	0.475	0.547
Cribra (absent or present)	0.847	0.932
Cribra (by type)	0.639	0.624

Pubic Symphysis recording

The same randomly selected individuals were used for pubic symphysis analysis as the non-metric trait analysis, however due to post-mortem damage the final number of observable pubic symphysis included in error rate statistics was 20 (a mix of left and right side). Of the randomly selected symphysis none were scored for eburnation at the time of original measurements, by the lead researcher months later or by the separate scorer therefore it has not been included here. A Cohen’s kappa analysis showed a range from poor to good with regards to intra- and inter- observer error rates (see Table 4-9). This low level of agreement is likely to be due to several reasons including; post-mortem damage being interpreted as traits and unclear describes leading to differing interpretations and lack of training prior to recording. These low repeatability rates should be considered when interpreting the results.

Table 4-9 Osteitis pubis recording criteria intra- and inter- observer error rates, Wharram Percy collection

Criteria	Intraobserver	Interobserver
Porosity	0.364	0.364
Irregularity	0.634	0.468
Osteophytes	0.643	0.146
Erosion	0.318	0.400

Chapter 5. Results I: Wharram Percy collection (WPC)

In this chapter the results of the statistical analysis of the Wharram Percy collection are presented. Descriptive statistics will be provided for each sample under statistical analysis. Not all femora could be used for all tests and therefore the number used will be presented each time.

Sections 5.1. and 5.2. provide an overview of the alpha angle and non-metric trait data for this sample and to determine if any additional factors are acting on these measurements, such as:

- Side
- Sex
- Age range category
- Offset ratio

Section 5.3. focuses on determining if there is a significant difference in alpha angle size dependent on the presence/absence of the non-metric traits; Poirier's facets, plaque and cribra. This will also be controlled by various factors including:

- Offset ratio
- Age range category
- Sex

The results in section 5.4. show the difference in proportions of femora with and without cam morphology (using three commonly used alpha angle thresholds from the literature ≥50°, ≥55°, ≥60°) by the presence of non-metric traits. Analysis has been performed for pooled sex, males only and females only.

Section 5.5. presents the results regarding side asymmetry of cam morphology. While section 5.6. shows if there is a difference in the proportion of cam morphology by sex.

5.1. Alpha angle information

Distribution of alpha angle size by side

The mean alpha angle size for the whole sample (n = 174) was 51.29°. The mean alpha angle for the left femora (n = 90) was 52.84˚ and 49.69˚ for the right (n= 84). Table 5-1 shows the descriptive statistics for alpha angle size when pooled by sex for; both sides together, left side only and right side only, while Figure 5-1 shows the distribution of alpha angles by side when pooled for sex for the Wharram Percy sample.

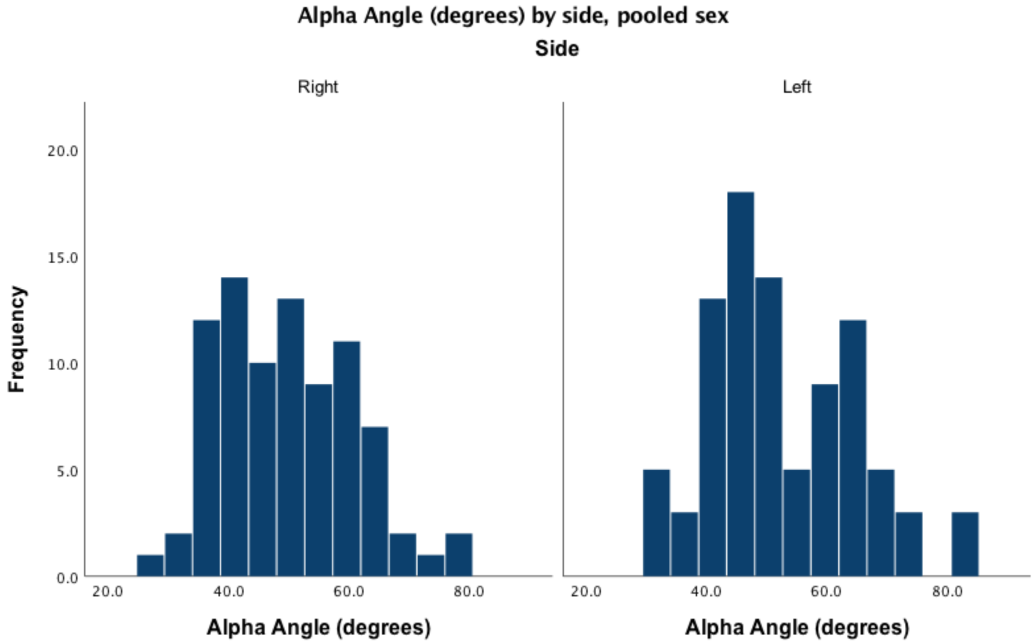


Figure 5-1 Distribution of alpha angles by side, pooled sex for the WPC

Table 5-1 Alpha angle descriptive statistics for pooled sex, WPC

Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev. (°)
Both Femora	174	54.01	28.63	82.63	51.29	11.62
Left Femora	90	50.70	31.93	82.63	52.84	12.17
Right Femora	84	50.72	28.63	79.35	49.69	11.10

Bilateral asymmetry of mean alpha angle size was determined using a paired sample t-test. Only individuals (n = 66) with alpha angles recorded on both femora were included. The left femora (53.04° ± 12.20°) had a higher mean alpha angle size than right femora (50.05° ± 10.50°) (Table 5-2), this difference was statistically significant, $t(65) = 2.98, p= 0.004, d= 0.3$ (Table 5-3).

Table 5-2 Paired sample descriptive statistics for left and right femora alpha angles, pooled sex, WPC

Side	N	Mean (°)	Std. Dev (°)	Std. Error Mean
Left femora	66	53.04	12.20	1.50
Right femora	66	50.05	10.50	1.29

Table 5-3 Paired sample t-test data table for alpha angle size by side, pooled for sex, WPC

	Paired differences							
				95% confidence interval				
Alpha angles	Mean	Std. dev	Std. error mean	Lower	Upper	t	df	Sig. (2-tailed)
Left side – right side	2.986	8.132	1.001	0.987	4.985	2.983	65	0.004

Alpha angle size by sex

The descriptive statistics for alpha angle size by sex and side are shown in Table 5-4 below. Due to the small number of femora for those recorded as female? they were excluded from statistical analysis of alpha angle size between sexes.

Table 5-4 Alpha angle descriptive statistics by sex for left femora only, right femora only and all femora, WPC

Sex	Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
Males	Right	53	47.67	31.68	79.35	52.48	10.90
	Left	59	50.70	31.94	82.63	54.64	11.81
	All	112	50.96	31.68	82.63	53.62	11.39
Females	Right	29	44.88	28.63	73.51	45.80	10.38
	Left	29	50.15	31.93	82.09	48.61	12.09
	All	58	53.46	28.63	82.09	47.21	11.26
Female?	Right	2	1.59	44.35	45.93	45.14	1.12
	Left	2	5.75	42.59	48.35	45.47	4.07
	All	4	5.75	42.59	48.35	45.30	2.44

An independent sample t-test showed (Table 5-5) for the left side, the mean alpha angle size was higher in the males, 54.64° ± 11.81°, than the females, 48.61° ± 12.09°. This difference was significant, $t\ (86) = 2.24,\ p = 0.028.$ For the right side, the mean alpha angle size was also significantly different between males (52.48° ± 10.90°) and females (45.80° ± 10.38°), *t(80) = 2.70, p = 0.008.* Figure 5-2 shows the difference in the distribution of alpha angle data between males and females for the left and right side separately.

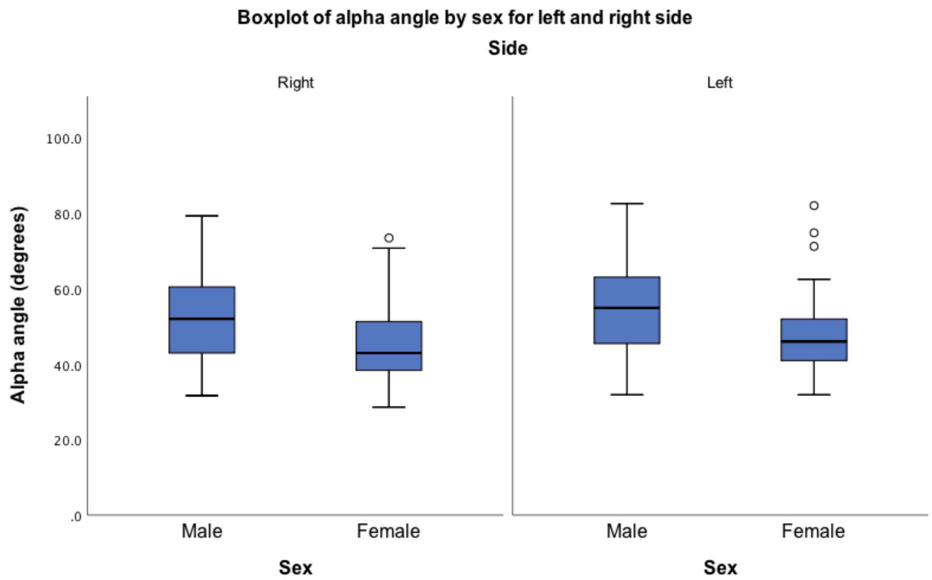


Figure 5-2 Boxplot of alpha angle data by sex for right and left side, WPC

Table 5-5 Independent sample t-test data table for alpha angle by sex for left and right side separately, WPC

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	2.235	86	0.028	6.031	2.699	0.666	11.396
Right side	2.698	80	0.008	6.682	2.476	1.754	11.611

Due to the significant difference found between males and females, paired sample t-tests were run for males and females separately, to establish if the difference in alpha angle size between the left and right femur observed for the whole sample was observed in males and/or females. Table 5-6 presents the descriptive statistics for this test and Table 5-7 the paired sample t-test data for males and females. Nineteen females had alpha angles recorded on both left and right femora. An extreme outlier was present therefore a comparison test was run excluding this case. This however did not impact conclusions; therefore, the original test was used. The mean alpha angle size was 2.63° ± 1.55° [mean ± std. error] higher for the left side compared to the right. This was not statistically significant, *t(19) = 1.698, p = 0.107.*

Forty-six males had alpha angles recorded for both left and right femora. The mean alpha angle size for the left femora (55.06° ± 12.31°) was 3.11° ± 1.30° [mean ± std. error] higher than for the right (51.95° ± 10.35°) femora, this difference was statistically significant, $t(45) = 2.401$, $p = 0.021$.

Table 5-6 Paired sample descriptive statistics for left and right alpha angles, for females and males, WPC

Sex	Side	N	Mean (°)	Std. Dev	Std. Error Mean
Female	Left	19	48.39	11.15	2.56
	Right	19	45.76	9.99	2.29
Male	Left	46	55.06	12.31	1.82
	Right	46	51.95	10.35	1.53

Table 5-7 Paired sample t-test data table for alpha angle size by side, for males and females separately, WPC

Alpha angles	Paired differences							
				95% confidence interval				
Left side – right side	Mean	Std. dev	Std. error mean	Lower	Upper	t	df	Sig. (2-tailed)
Females only	2.628	6.747	1.548	-0.623	5.880	1.698	18	0.107
Males only	3.111	8.787	1.296	0.502	5.720	2.401	45	0.021

Alpha angle size by age range category

The information regarding age was provided by collection curator in estimated ranges. These ranges were not consistent, therefore, the median age was taken from these ranges and placed into one of three age groups, 18-29 years, 30-49 years and 50+ years. Several individuals had ADULT listed, therefore they were excluded from analysis incorporating age. This produced the distribution shown in Table 5-8 below. The distribution of individuals per age category by sex is shown in Figure 5-3.

Table 5-8 Number of individuals and femora per age category, WPC

Age Ranges	Number of males	Number of females	Number of female?	Number of individuals	Number of femora	Percentage of femora
18-29 years	12	12	1	25	50	22.5%
30-49 years	21	19	2	42	84	36.9%
50+ years	21	8	0	29	58	27%
Indeterminate	14	1	0	15	30	13.5%
Total	69	40	3	111	222	100.0%

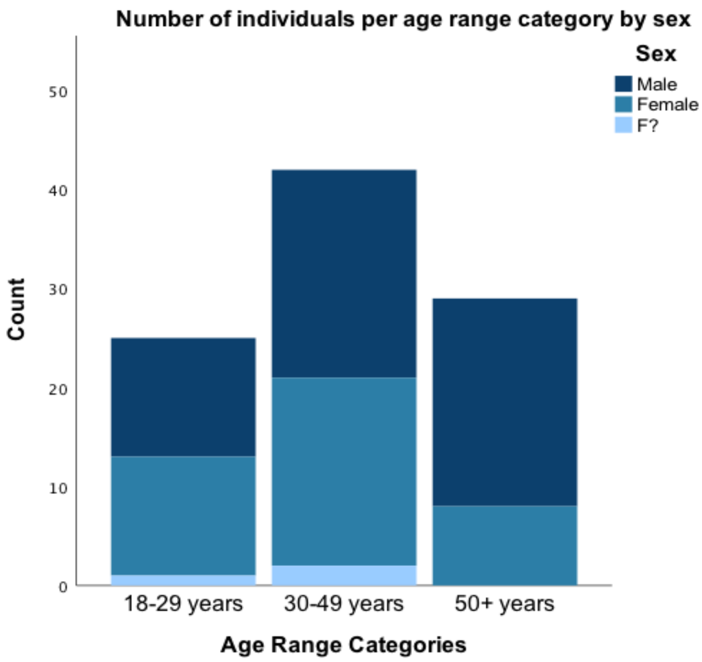


Figure 5-3 Clustered bar chart of number of individuals per age range by sex, WPC

The descriptive statistics for alpha angle size per age range category is shown in Table 5-9. When a one-way ANOVA was run to determine if alpha angle size was significantly different between each age range category (pooled for sex) for left side, an extreme outlier was present for the 18-29 years age group data. With the outlier present the mean alpha angle size increased from 18-29 years group (47.02° ± 9.49°) to 30-49 years group (52.01° ± 11.42°) to 50+ years group (55.00° ± 11.72°). This was not found to be significant, $F(2, 73) = 3.075, p = 0.052, \eta^2=0.078$. Due to the extreme outlier, the test was rerun excluding this data point to determine if its presence had an impact on conclusions. With the outlier excluded for the comparison test, there was still an increase in mean alpha angle size from 18-29 years (45.69° ± 7.35°) to 30-49 years to 50+ years. The assumption of homogeneity of variances was however violated (p = 0.018) with this outlier excluded, therefore a Welch's ANOVA was run. This found a significant difference between age groups, *Welch's* $F(2, 46.916) = 6.099, p= 0.004$. The Games-Howell post hoc test found the significant difference to be between 18-29 years and 50+ years groups *(*$p = 0.007$*).* This extreme outlier is an individual whose age estimate from the curator was 21-25. This is at the upper end of the 18-29 years age bracket. In addition to this, it is common biological age estimates are not 100% accurate and therefore this case could be an extreme outlier as it would be better represented in an older age category.

For the right side, there was also an increase in alpha angle size with increase in age from 18-29 years (46.93° ± 10.97°) to 30-49 years (48.49° ± 8.52°) to 50+ years (53.40° ± 10.99°). This difference was not statistically significant, *$F(2, 71) = 2.541$, $p=0.086$, $\eta^2= 0.067$.*

Table 5-9 Alpha angle descriptive statistics per age category and femoral side, WPC

Age range	Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
18-29 years	Right	19	44.88	28.63	73.51	46.93	10.97
	Left	22	42.93	31.93	74.87	47.02	9.49
	All	41	46.24	28.63	74.87	46.97	10.08
30-49 years	Right	32	27.11	35.66	62.77	48.49	8.52
	Left	30	48.57	32.70	81.27	52.01	11.42
	All	62	48.57	32.70	81.27	50.19	10.10
50+ years	Right	23	46.70	32.65	79.35	53.40	10.99
	Left	24	50.15	31.94	82.09	55.00	11.72
	All	47	50.15	31.94	82.09	54.22	11.28

Due to the significant difference in alpha angle size between males and females, two-way ANOVAs were run to determine if there was an interaction effect between sex and age range category on mean alpha angle size. Individuals categorised as female? and indeterminate for age were excluded from this analysis.

For the right side the interaction effect between sex and age range category on alpha angle was not significant, *$F(2,66)= 1.668$, $p=0.196$, partial $\eta^2= 0.048$*. There was also no significant effect of age range category or sex on alpha angle size. The data for males in the 30-49 years group was not normally distributed, however, it was not possible to transform the data to reach normality without violating normality for other variables.

For the left side the interaction effect between sex and age range category on alpha angle was not significant, *$F(2,68)= 1.161$, $p=0.319$, partial $\eta^2= 0.033$.* Main effect analysis showed there was no significant impact of age range category, *$F(2,68)=2.102$, $p= 0.130$* or sex, *$F(1,68)= 1.285$, $p=0.261$,* on alpha angle size. There was, however, an extreme outlier present for the males in the 18-29 years age range category, therefore a comparison test was run excluding this outlier. This did not however affect the conclusions for this test.

Correlation between alpha angle size and offset ratio

A Spearman's correlation showed a statistically significant moderate negative correlation was found between offset ratio and alpha angle size on the right side, *r(74) = -0.523, p = <0.0005.* Figure 5-4 shows the relationship between alpha angles and offset ratios for the right side.

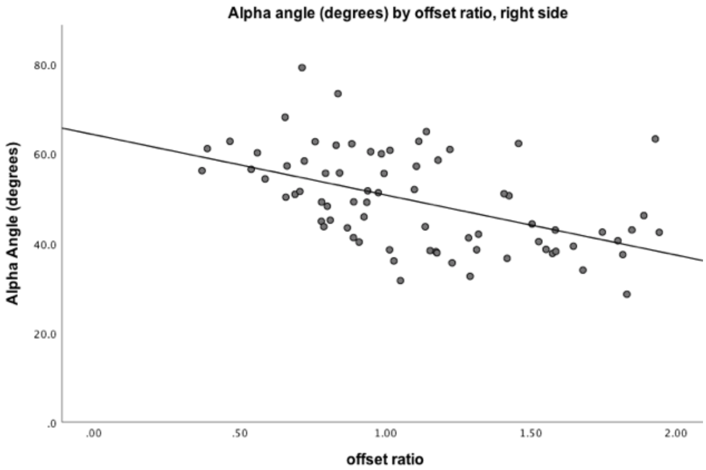


Figure 5-4 Scatterplot of alpha angle against offset ratio, right side only, pooled for sex, WPC

For the left side, a statistically significant weak negative correlation was found between offset ratio and alpha angle size, *r(82) = -0.386, p = <0.0005.* Figure 5-5 shows the relationship between alpha angles and offset ratios for the left side.

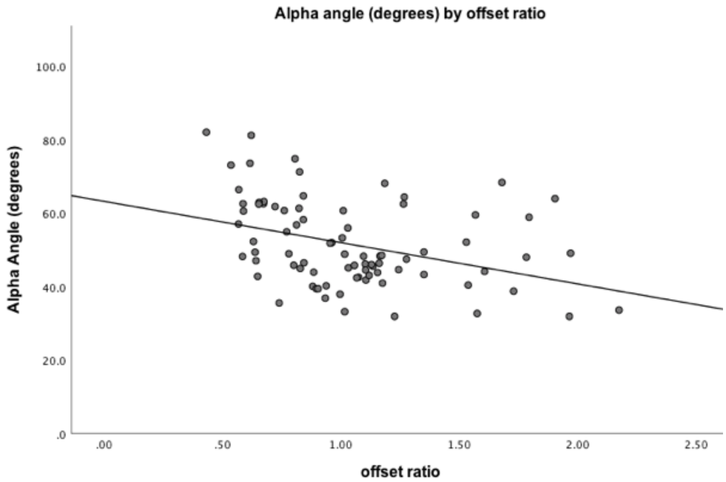


Figure 5-5 Scatterplot of alpha angle against offset ratio, left side only, pooled for sex, WPC

These results indicate, as the head becomes less concaved anteriorly (increased alpha angle size) it becomes more posteriorly orientated.

5.2. Prevalence of non-metric traits

Poirier's facets

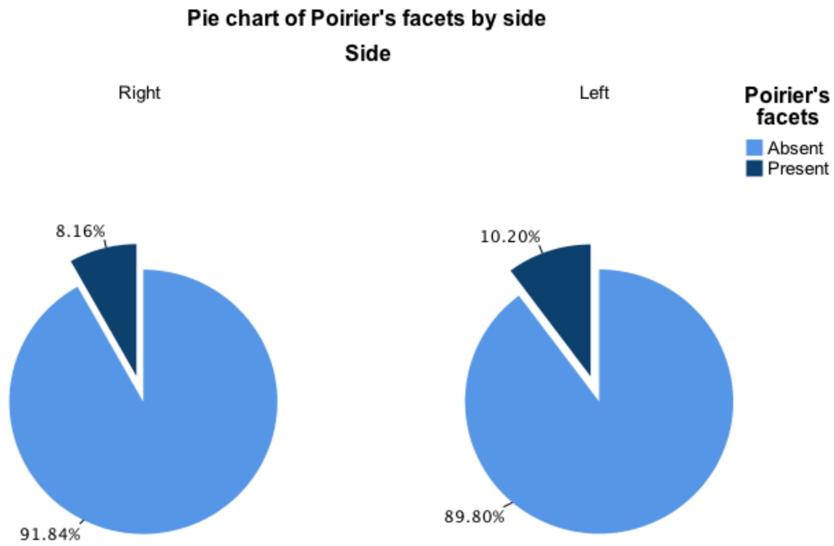


Figure 5-6 Pie charts of distribution of Poirier's facets in observable femora for left and right sides, pooled for sex, WPC

Of the 222 femora analysed, Poirier's facets were present on 18 (9% of observable femora), absent on 178 (91% of observable femora) and unobservable due to post-mortem damage on 26 femora (Figure 5-6 presents the percentage of femora with and without Poirier's facets, excluded those classified as unobservable). Table 5-10 presents the number and percentage of Poirier's facets present and absent per femur by side and pooled for sex.

Table 5-10 Prevalence of Poirier's facets on the observable femora by side, pooled sex, WPC

Femora side	Total no. femur	No of femur unobservable for Poirier's facets	No of femur with Poirier's facets present	% of observable femur with Poirier's facets present	No of femur with Poirier's facets absent	% of observable femur with Poirier's facets absent
Left	111	13	10	10.20	88	89.80
Right	111	13	8	8.16	90	91.84
Total	222	26	18	9.14	178	90.86

A total of 86 individuals had both femora present and analysed for the presence of Poirier's facets (Table 5-11). Of these, 75 (87.2%) individuals were absent for Poirier's facets on both sides, 7 (8.1%) individuals had bilateral Poirier's facets present, 3 (3.5%) individuals had Poirier's facets present on left but absent on right, 1 (1.2%) individual had Poirier's facets present on right but absent on left.

Table 5-11 cross tabulation of the occurrence of Poirier's facets by left and right side, WPC

Poirier's facets		Right Side		
		Present	Absent	Total
Left Side	Present	7	3	10
	Absent	1	75	76
	Total	8	78	86

With regards to sex, 13% of observable male femora and 2.9% of observable female femora had Poirier's facet present. Of the Poirier's facets present in the sample, 88.9% were recorded on male and 11.1% on female femora. Table 5-12 shows the number of femora between males, females and female?.

Table 5-12 Count of femora categorised for the presence or absence of Poirier's facets by sex and side, WPC

Sex	Side	Absent	Present	Unobservable	Total
Male	Left	55	8	5	68
	Right	52	8	8	68
	Total	**107**	**16**	**13**	**136**
Female	Left	31	2	7	40
	Right	36	0	4	40
	Total	**67**	**2**	**11**	**80**
Female?	Left	2	0	1	3
	Right	2	0	1	3
	Total	**4**	**0**	**2**	**6**
Total		**178**	**18**	**26**	**222**

There was not a considerable difference between each age range category and the presence of Poirier's facets. For the 18-29 years category, only 1 femur (2.2%) had Poirier's facet recorded as present, 7 femora (10.1%) were recorded as having Poirier's facets present in the 30-49 years category and 7 femora (12.7%) were recorded in the 50+ years categories. Table 5-13 shows the distribution of femora categorised for the presence or absence of Poirier's facets, pooled for side and sex.

Table 5-13 Count of femora categorised for presence or absence of Poirier's facets by age range category, WPC

Age group	Absent	Present	Unobservable	Total
18-29 years	45	1	4	50
30-49 years	62	7	13	82
50+ years	48	7	5	60
Indeterminate	23	3	4	30
Total	**178**	**18**	**26**	**222**

Plaque

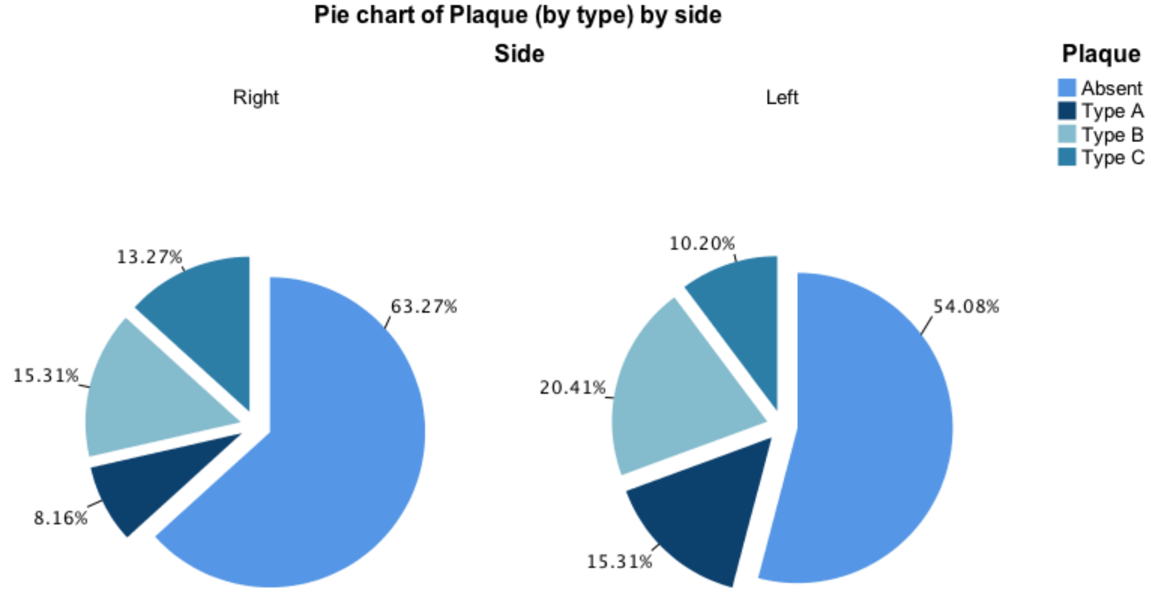


Figure 5-7 Pie charts of distribution of plaque, by type, recorded on observable femora for left and right side, pooled for sex

Of 222 femora analysed, plaque was present on 81 (41.3% of observable femora), absent on 115 (58.7% of observable femora) and unobservable on 26 femora. Table 5-14 shows the prevalence of plaque by side and by total, pooled for sex, while Figure 5-7 shows the rates of each plaque type by side.

Table 5-14 Prevalence of plaque, by type, on observable femora by side, pooled sex, WPC

Total			Observable femora											
			Type A			Type B			Type C			Absent		
Side	Total no. femur	N of unobserv femur	N	% of total	% for side	N	% of total	% for side	N	% of total	% for side	N	% of total	% for side
Left	111	13	15	7.7	15.3	20	10.2	20.4	10	5.1	10.2	53	27.0	54.1
Right	111	13	8	4.1	8.2	15	7.7	15.3	13	6.6	13.3	62	31.6	63.3
Total	222	26	23	11.7	11.7	35	17.9	17.9	23	11.7	11.7	115	58.7	58.7

N = number of femora

A total of 86 Individuals had both femora present and observable for the presence of plaque. Table 5-15 shows the cross tabulation for the occurrence of plaque on the left side and right side, with 50.0% (43/86) of individuals were recorded as not having plaque present on either side. Type A plaque occurred unilaterally in 7/86 individuals and bilaterally in 3/86 individuals. While type B and C occurred more commonly bilaterally, 10/86 and 6/86 respectively.

Table 5-15 cross tabulation of the occurrence of plaque by left and right side, WPC

Type		Right side				
		A	B	C	Absent	Total
Left side	A	3	1	0	6	10
	B	2	10	2	4	18
	C	1	0	6	2	9
	Absent	1	2	3	43	49
	Total	7	13	11	55	86

When considering the distribution of plaque by sex, 48% of observable male femora and 29% of female femora had plaque present. Table 5-16 shows the distribution of plaque by sex and side. For males, type A was recorded on 17% of femora, type B on 20% and type C on 11% of femora. For females, type A was present on 3% of femora, type B on 15% and type C on 12% of observable femora.

Table 5-16 Distribution of plaque (by type) by sex and side, WPC

Sex	Side	Absent	Type A	Type B	Type C	Unobservable	Total
Male	Left	27	14	15	7	5	68
	Right	37	7	10	6	8	68
	Total	**64**	**21**	**25**	**13**	**13**	**136**
Female	Left	25	1	5	2	7	40
	Right	24	1	5	6	4	40
	Total	**49**	**2**	**10**	**8**	**11**	**80**
Female?	Left	1	0	0	1	1	3
	Right	1	0	0	1	1	3
	Total	**2**	**0**	**0**	**2**	**2**	**6**
Total		**115**	**23**	**35**	**23**	**26**	**222**

With regards to the distribution of plaque by age range category, there was an increase in the number of femora with plaque present from 18-29 years, to 30-49 years, to 50+ years (see Table 5-17). When considering rates of each plaque type per age range category, the 18-29 years had the highest rates of type C, 30-29 years had the highest rates of type B and 50+ had the highest rates of type A (see Tables 5-18 and 5-19).

Table 5-17 Count of femora categorised for plaque type by age group, pooled sex, WPC

Age group	Absent	Type A	Type B	Type C	Unobservable	Total
18-29 years	32	4	1	9	4	50
30-49 years	48	6	8	9	13	84
50+ years	23	8	19	3	5	58
Indeterminate	12	5	7	2	4	30
Total	**115**	**23**	**35**	**23**	**26**	**222**

Table 5-18 Percentage of femora within each age group category by plaque type, pooled sex, WPC

Age group	% of observable femora absent for Plaque within age group	% of observable femora present for Type A within age group	% of observable femora present for Type B within age group	% of observable femora present for Type C within age group
18-29 years	69.6%	8.7%	2.2%	19.6%
30-49 years	67.6%	8.5%	11.3%	12.7%
50+ years	43.4%	15.1%	35.8%	5.7%

Table 5-19 Percentage of femora for each plaque type by age range category, pooled sex, WPC

Age group	% of observable femora absent for Plaque between age group	% of observable femora present for Type A between age group	% of observable femora present for Type B between age group	% of observable femora present for Type C between age group
18-29 years	31.1%	22.2%	3.6%	42.9%
30-49 years	46.6%	33.3%	28.6%	42.9%
50+ years	22.3%	44.4%	67.9%	14.3%

Cribra

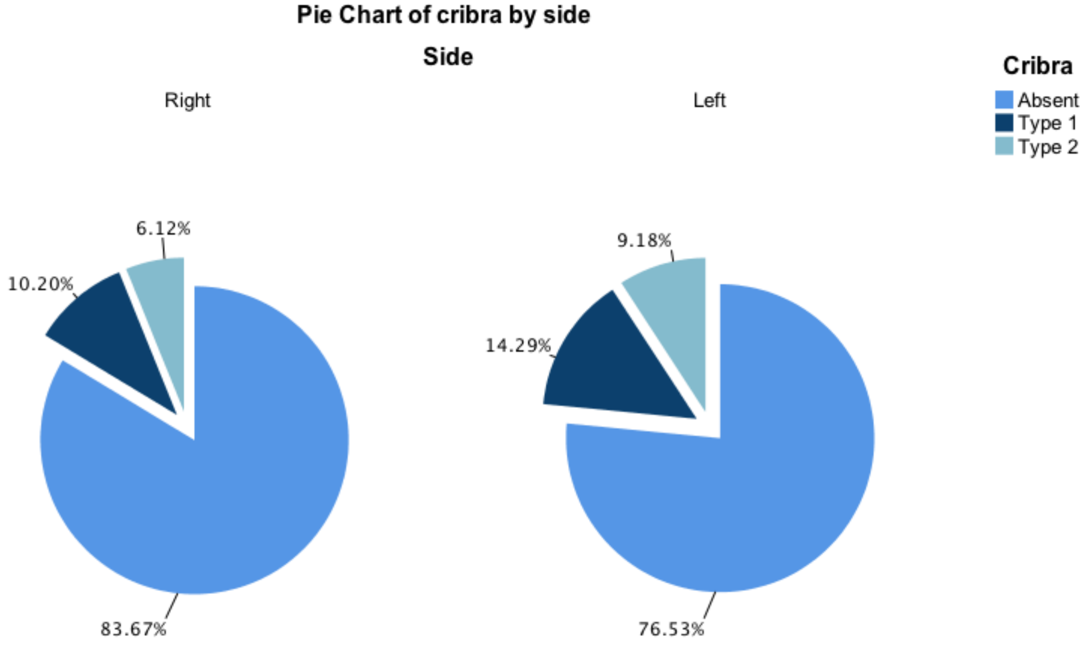


Figure 5-8 Pie chart of cribra (by type) by side, pooled sex, WPC

Of 222 femora analysed, cribra was present on 39, absent on 157 and unobservable 26 femora. Of 39 femora with cribra, 24 (62%) had type 1, 15 (38%) had type 2. For the left side cribra was present on 23 femora, of which type 1 was present on 14 and type 2 was present on 9 femora. For the right side cribra was present on 16 femora of which 10 were type 1 and 6 were type 2. Figure 5-8 shows the rates of cribra per side and Table 5-20 shows the prevalence of cribra (by type) by side and total.

Table 5-20 Prevalence of cribra on observable femora by side, pooled sex, WPC

Total			Observable								
			Type I			Type II			Absent		
Side	Total no. femur	N of unobserv femur	N	% of total	% for side	N	% of total	% for side	N	% of total	% for side
Left	111	13	14	7.1	14.3	9	4.6	9.2	75	38.3	76.5
Right	111	13	10	5.1	10.2	6	3.1	6.1	82	41.8	83.7
Total	222	26	24	12.2	12.2	15	7.7	7.7	157	80.1	80.1

A total of 86 individuals had both femora present and analysed for the presence of cribra (Table 5-21). Of these, 74.4% (64) of individuals were absent for cribra on both femora. While 9.3% (8) individuals had bilateral type I cribra and 3.5% (3) individuals had bilateral type II cribra. Cribra was present bilaterally more commonly than unilaterally in this sample.

Table 5-21 cross tabulation of the occurrence of cribra by left and right side, WPC

	Type	Right side			
		I	II	Absent	Total
Left side	I	8	1	4	7
	II	0	3	4	13
	Absent	1	2	63	66
	Total	9	6	71	86

When analysing the distribution of cribra by sex, 19.5% (24/123) and 21.7% (15/69) of observable males and female femora, respectively, had either type I or type II recorded as present (See Table 5-22).

Table 5-22 Count of femora categorised for the presence or absence of cribra by sex and side, WPC

Sex	Side	Absent	Type I	Type II	Unobservable	Total
Male	Left	49	10	4	5	68
	Right	50	7	3	8	68
	Total	**99**	**17**	**7**	**13**	**136**
Female	Left	24	4	5	7	40
	Right	30	3	3	4	40
	Total	**54**	**7**	**8**	**11**	**80**
Female?	Left	2	0	0	1	3
	Right	2	0	0	1	3
	Total	**4**	**0**	**0**	**2**	**6**
Total		**157**	**24**	**15**	**26**	**222**

The prevalence of femora with cribra present decreased as age group increased from; 18-29 years 37.0% of observable femora had cribra present, 30-49 years for 15.5% and for the 50+ years group 11.3% of observable femora had cribra present (Table 5-23). The prevalence rates of cribra per age range categories is shown in Tables 5-24 and 5-25.

Table 5-23 Count of femora categorised for cribra type by age group, WPC

Age group	Absent	Type I	Type II	Unobservable	Total
18-29 years	29	11	6	4	50
30-49 years	58	6	5	13	82
50+ years	49	4	2	5	60
Indeterminate	21	3	2	4	30
Total	**157**	**24**	**15**	**26**	**222**

Table 5-24 Percentage of femora within each age range category by cribra (by type), pooled sex and side, WPC

Age group	% of observable femora absent for cribra within age group	% of observable femora present for Type I within age group	% of observable femora present for Type II within age group
18-29 years	63.0%	23.9%	13.0%
30-49 years	84.5%	8.5%	7.0%
50+ years	88.7%	7.5%	3.8%

Table 5-25 Percentage of femora with/without cribra (by type) by age range category, pooled sex and side, WPC

Age group	% of observable femora absent for cribra between age group	% of observable femora present for Type I between age group	% of observable femora present for Type II between age group
18-29 years	21.3%	52.4%	46.2%
30-49 years	44.1%	28.6%	38.5%
50+ years	34.6%	19.0%	15.4%

5.3. Alpha angle size and non-metric traits

This section is focused on determining if there was a difference in mean alpha angle size between femora with and those without non-metric traits present. In addition to this, analysis to establish if femoral head translation (through offset ratio) had an impact on this has been included. Due to the difference in the proportion of femora with non-metric traits present between the age range categories, analysis was carried out to determine if there was an interaction effect between age range category and the presence of non-metric traits on alpha angle size. Owing to the significant difference in alpha angle size between males and females, analysis was also performed for pooled sex and then for males and females separately. This also allowed the male data to be directly comparable to the LLC data, as only males were analysed for this sample.

Poirier's facets

Pooled sex

For the right side there was a significant difference in mean alpha angle size between those with Poirier's facets present (60.44° ± 3.30°) and absent (49.03° ± 11.07°), $t(81) = -2.702, p = <0.0005$. The left side also showed a significant difference in mean alpha angle size between those with Poirier's facets present (66.90° ± 12.10°) and absent (50.77° ± 11.10°), $t(86) = -4.093, p = <0.0005$. Figure 5-9 shows the distribution of alpha angles for femora with and without Poirier's facets for left and right separately. Table 5-26 shows the descriptive statistics for alpha angle size by Poirier's facets and side.

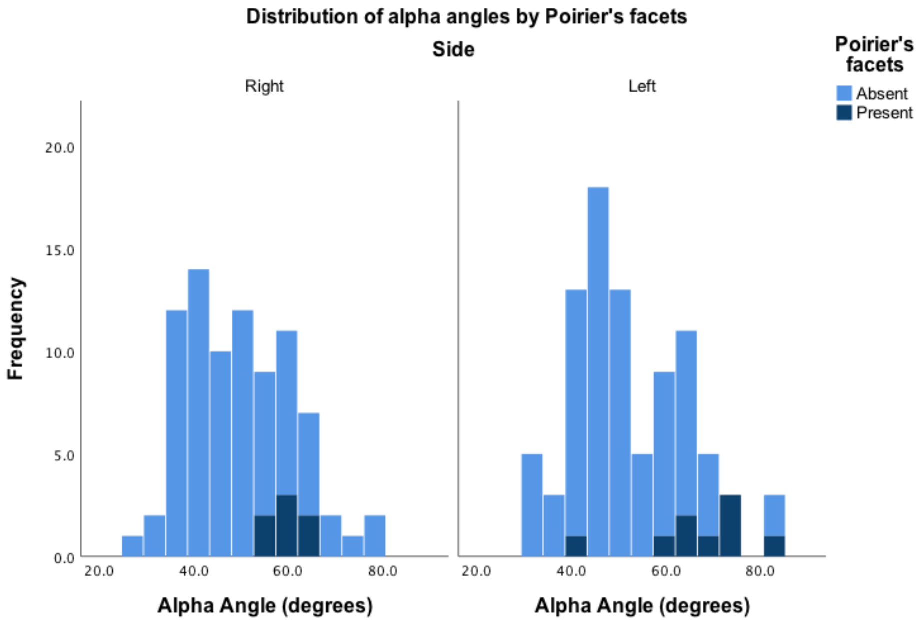


Figure 5-9 Stacked histogram of the distribution of alpha angles with and without Poirier's facets, for right and left side, pooled sex, WPC

Table 5-26 Descriptive statistics for alpha angle size when split by femoral side and presence/absence of Poirier's facets, pooled sex, WPC

Side	Poirier's facets	N	Mean (°)	Min. (°)	Max. (°)	Range (°)	Std. Dev. (°)
Left Femora	Absent	79	50.77	31.93	82.63	50.70	11.10
	Present	9	66.90	39.48	81.27	41.79	12.10
Right Femora	Absent	76	49.03	28.63	79.35	50.72	11.07
	Present	7	60.44	56.11	65.02	8.91	3.30

When adjusted for femoral head translation (offset ratio), for the right side there was still a statistically significant difference in alpha angle size between femora with and without Poirier's facets, $F(1, 71)=4.041, p= 0.048, \text{partial } \eta^2=0.054$ (Figure 5-10). The standardized residuals for alpha angle data were not normally distributed for the Poirier's facets absent group (*p=0.045),* therefore a comparison test with transformed data was run. The comparison test did not find a significant difference in mean alpha angle size after adjusting for offset ratio, $F(1, 71)=3.957$, $p=0.051$, partial $\eta^2=0.053$.

For the left side, there was still a statistically significant difference in alpha angle size between femora with and without Poirier's facets when adjusted for offset ratio, $F(1, 77)=13.877$, $p<0.0005$, partial $\eta^2=0.153$ (Figure 5-10). The standardized residuals for alpha angles data were not normally distributed for Poirier's facets present group ($p = 0.044$), therefore a comparison test was run with transformed data. This did not affect the conclusions made with the original data test.

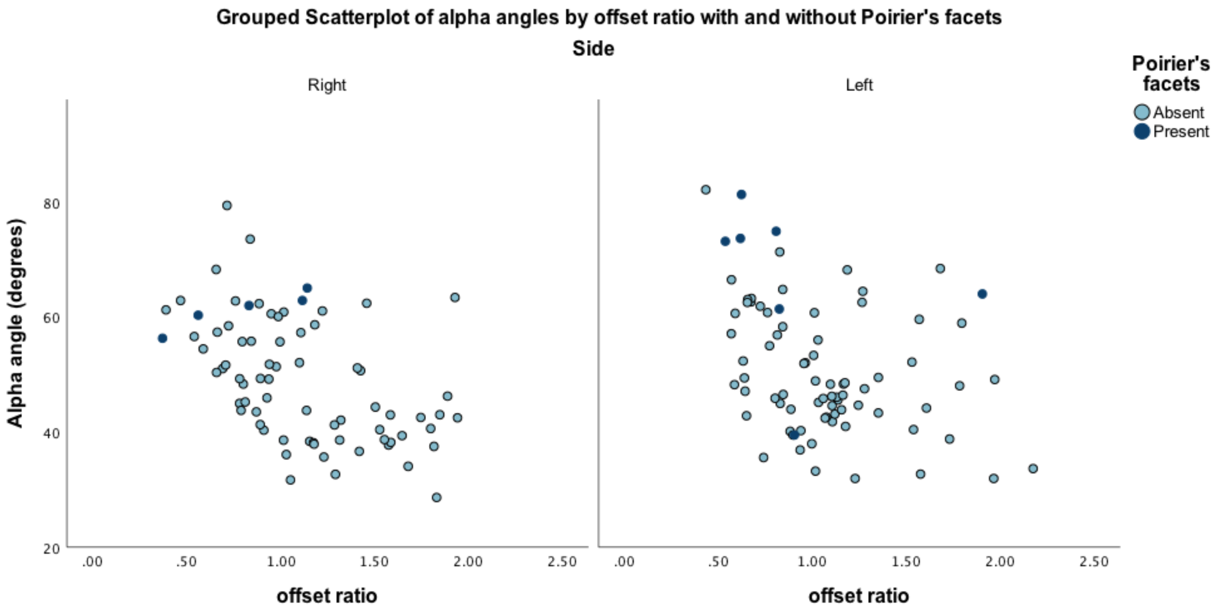


Figure 5-10 Grouped scatterplot of alpha angles by offset ratio for femora with/without Poirier's facets, pooled sex, WPC

To determine if age had an impact on the mean alpha angle size between femora with or without Poirier's facets two-way ANOVAS were run. For the right side, there was no statistically significant interaction between age range category and Poirier's facets on alpha angle size, $F(1,68)=0.000$, $p=0.996$. Main effect analysis showed a statistically significant impact of Poirier's facets on alpha angle size $F(1,68)=5.825$, $p=0.019$ but not age range category $F(2,68)=1.320$, $p=0.274$. The left side also showed no statistically significant interaction between age range category and Poirier's facets on alpha angle size, $p=0.299$. Main effect analysis showed a statistically significant impact of Poirier's facets on alpha angle size $F(1,68)=18.277$, $p= <0.0005$ but not age range category $F(2,68)=1.350$, $p=0.266$.

Males only

When splitting the sample by sex, for males, a similar result to the pooled sex sample was shown with the mean alpha angle size being significantly higher for those with Poirier's facets on the left side (69.98 ± 7.10°) than those without (52.49 ± 10.95°), *$t(55) = -4.019$, $p = <.0005$).* The right side also showed a statistically higher mean alpha angle size for femora with Poirier's facets compared to those without, 60.44˚± 3.30 and 51.29˚± 11.28 respectively, *$t(32.897) = -4.370$, $p = <0.0005$.*

After adjusting for offset ratio, there was no significant difference in alpha angle size between femora with and without Poirier's facets on the right side, *$F(1, 44)= 3.002$, $p= 0.090$, partial $\eta^2=0.064$.* While for the left side there was a statistically significant difference in alpha angle size between femora with and without Poirier's facets, *$F(1, 47)= 17.595$, $p <0.0005$, partial $\eta^2=0.272$.*

Females only

For females, there was a difference in alpha angle size for those with Poirier's facets, 57.17° compared to those without, 46.85° as can be found in the male femora. There were however only 2 female femora with Poirier's facets present; therefore, it was not possible to determine if this difference was significant.

Plaque

Pooled sex

The descriptive statistics for alpha angle size by plaque type are shown in Table 5-27 below and the distribution of alpha angles by plaque type is shown in Figure 5-11. For pooled sex, on the right side, the alpha angle size decreased from plaque type A (64.50° ± 10.42°) to type B (53.81° ± 11.17°) to type C (44.09° ± 8.09°), while those with plaque absent had a mean alpha angle size of 48.07° ± 9.90°. The alpha angle size was statistically significantly different for different plaque type groups, *$F(3, 79) = 7.299$, $p = <0.0005$, $\eta^2 = 0.217$*. Tukey post hoc analysis showed that the increase in alpha angle size was statistically significant from type A to absent (16.43° ± 4.02°) [mean ± std. error] (*$p = 0.001$*), type A to type C (20.42° ± 5.04°) (*$p = 0.001$*).

For the left side, the alpha angle size decreased from plaque type A (58.68° ± 12.63°) to type B (56.58° ± 10.67°) to type C (46.49° ± 7.76°), while those without plaque present had a mean alpha angle size of 50.33° ± 12.31°. The alpha angle size was statistically significantly different for different plaque type groups, $F\ (3,\ 84) = 3.151,\ p = 0.029,\ \eta^2 = 0.101$, however the post hoc test did not distinguish a difference between groups.

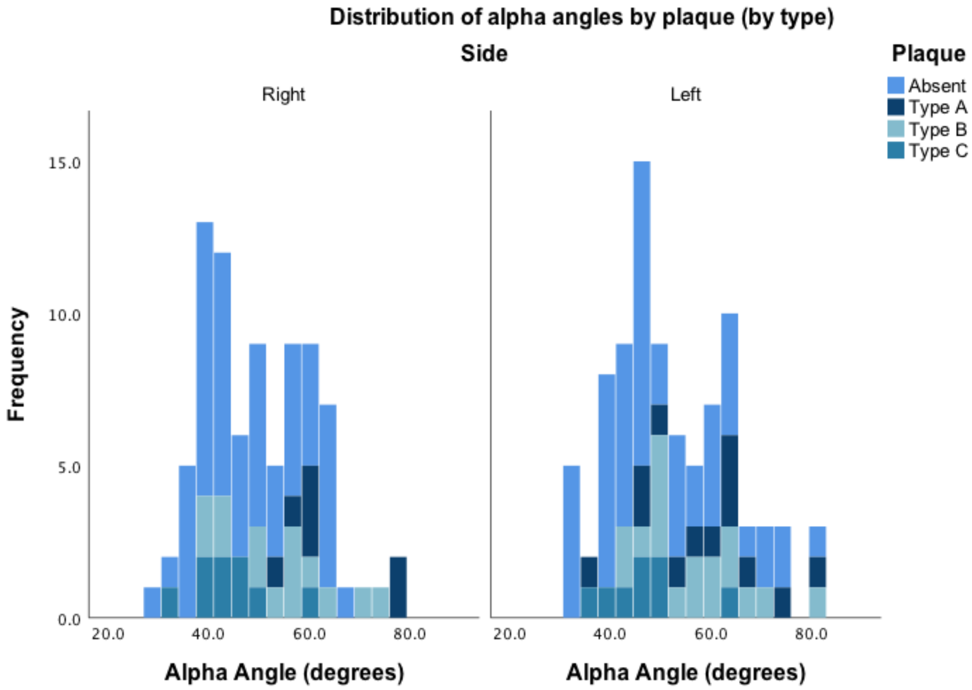


Figure 5-11 Stacked histogram of the distribution of alpha angles with and without Plaque (by type), for right and left side, pooled sex, WPC

Table 5-27 Descriptive statistics for alpha angle size when split by femoral side and presence/absence of plaque, WPC

Plaque	Side	N	Mean (°)	Std. Dev.	Std. error	Min. (°)	Max. (°)
Absent	Left	50	50.33	12.31	1.74	31.93	81.27
	Right	53	48.07	9.90	1.36	28.63	68.24
	All	103	49.17	11.14	1.10	28.63	81.27
Type A	Left	13	58.68	12.63	3.50	35.57	82.63
	Right	7	64.50	10.42	3.94	54.44	79.35
	All	20	6.72	11.97	2.68	35.57	82.63
Type B	Left	17	56.58	10.67	2.59	42.42	82.09
	Right	14	53.81	11.17	2.99	38.14	73.51
	All	31	55.37	10.81	1.94	38.14	82.09
Type C	Left	8	46.49	7.76	2.74	36.88	63.01
	Right	9	44.01	8.09	2.70	31.68	60.05
	All	17	45.22	7.78	1.89	31.68	63.01

When adjusted for femoral head translation (Figure 5-12), for the right side, there was no significant difference in alpha angle size between femora with (by type) and without plaque, $F(3, 69)= 2.129$, $p= 0.104$, partial $\eta^2=0.085$. For the left side there was also no significant difference $F(3, 75)= 1.181$, $p= 0.323$, partial $\eta^2=0.045$.

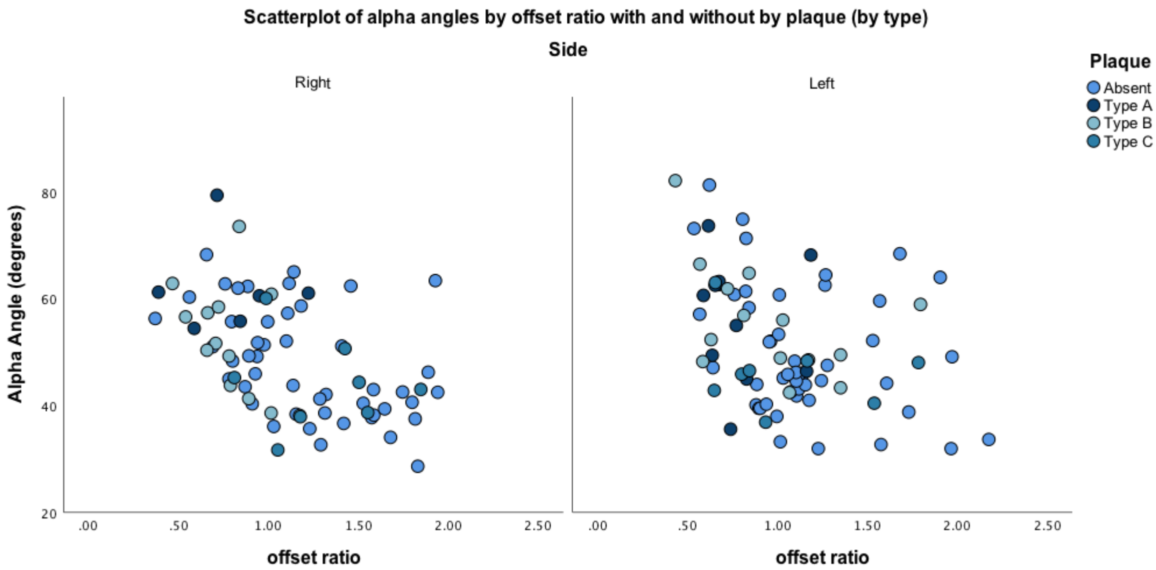


Figure 5-12 Grouped scatterplot of alpha angles by offset ratio for femora with/without plaque (by type), pooled sex, WPC

For the right side, there was a statistically significant interaction between age range category and plaque on alpha angle size, $p = 0.048$. There was a statistically significant difference in mean alpha angle size between age range categories for femora with type B plaque only, $F(2,61)= 3.324$, $p= 0.043$, partial $\eta^2=0.098$ .The mean alpha angle for femora with type B plaque present was significantly higher for those in the 18-29 years age category when compared to those in the 50+ years age category, $p = 0.049$. When adjusted for Bonferroni correction this was statistically significant however there was only 1 femur with type B plaque present in the 18-29 years group and therefore is likely to affect the results of this statistical test.

The left side showed no statistically significant interaction between age range category and plaque on alpha angle size, $p = 0.78$. For this side there was no femora present in the 18-29 years category with type B plaque.

Males only

For the right side, the alpha angle size decreased from plaque type A (65.08° ± 11.30°) to type B (51.41° ± 8.91°) to type C (45.11° ± 11.03°), while those with plaque absent had a mean alpha angle size of 51.63° ± 10.09°. The alpha angle size was statistically significantly different for different plaque type groups, $F\ (3, 48) = 4.094,\ p = 0.011,\ \eta^2 = 0.204$. Tukey HSD post hoc analysis showed that the increase in alpha angle size were statistically significant from type A and absent (13.45° ± 4.50°) [mean ± std. error] ($p = 0.022$), type A and type C (19.98° ± 6.13°) ($p = 0.011$).

For the left side the alpha angle size decreased from plaque type A (60.61° ± 11.02°), to type B (55.81° ± 9.00°) to type C (45.92° ± 9.10°), while those with plaque absent had a mean alpha angle size of 53.13° ± 13.27°. The alpha angle size was not statistically significantly different for different plaque types, $F\ (3, 53) = 2.413,\ p = 0.077,\ \eta^2 = 0.120$.

A one-way ANCOVA was run to determine if there was still a statistically significant difference in alpha angle size between those with and without Plaque and by type while controlling for offset ratio for the males only. For the right side after adjusting for offset ratio there was no significant difference in alpha angle size between femora with and without plaque, $F(3, 42)= 1.550,\ p= 0.216$, *partial* $\eta^2=0.100$. For the left side there was also no significant difference $F(3, 45)= 1.525,\ p= 0.221$, *partial* $\eta^2=0.092$.

Cribra

Pooled sex

The descriptive statistics for alpha angle size by cribra type are shown in Table 5-28 below. To determine if alpha angle size was significantly different between femora with cribra type I, II or absent, one-way ANOVA tests were conducted, Figure 5-13 shows the distribution of alpha angles by cribra type. For the right side, the alpha angle size was lower for type I (42.16° ± 8.95°) than for type II (53.19° ± 11.74°). Femora absent for cribra had a higher alpha angle than those with type I but lower than those with type II (50.82° ± 11.03°). The alpha angle size was not significantly different, $F\ (2, 80) = 2.716,\ p = 0.072,\ \eta^2 = 0.064$.

For the left side, the alpha angle size was lower for type I (48.33° ± 13.73°) than for type II (50.13° ± 12.62°). Those without cribra had a higher mean alpha angle size than those with either type present (53.46° ± 11.82°). The alpha angle size was not statistically significantly different between cribra types, $F\ (2, 85) = 1.085$, $p = 0.343$, $\eta^2 = 0.025$.

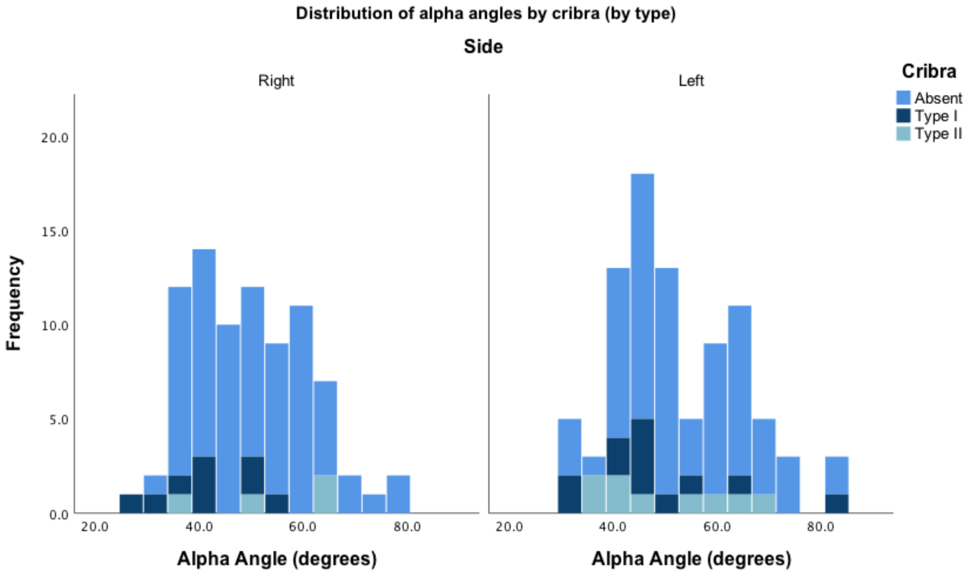


Figure 5-13 Stacked histogram of the distribution of alpha angles with and without Cribra (by type), for right and left side, pooled sex, WPC

Table 5-28 Descriptive statistics for alpha angle size when split by femoral side and presence/absence of cribra, pooled sex, WPC

Plaque	Side	N	Mean (°)	Std. Dev.	Std. error	Min. (°)	Max. (°)
Absent	Left	67	53.46	11.82	1.44	31.94	82.09
	Right	70	50.82	11.03	1.32	32.65	79.35
	All	137	52.11	11.45	0.98	31.94	82.09
Type I	Left	12	48.33	13.73	3.96	31.93	82.63
	Right	9	42.16	8.95	2.98	28.63	55.78
	All	21	45.68	12.07	2.63	28.63	82.63
Type II	Left	9	50.13	12.62	4.21	36.88	70.42
	Right	4	53.19	11.74	5.87	37.75	62.37
	All	13	51.07	11.95	3.31	36.88	70.42
Type I & Type II total	Left	21	49.10	12.97	2.83	31.93	82.63
	Right	13	45.55	10.77	2.99	28.63	62.37
	All	34	47.74	12.13	2.08	28.63	82.63

The independent sample t-tests (Table 5-29) showed for the left side there was no significant difference in mean alpha angle size between those with cribra present

(49.10° ± 12.97°) and absent (53.46° ± 11.82°), *t(86) = -1.442, p = 0.153* and for the right side only there was also no significant difference, *t(81) = -1.587, p = 0.116.*

Table 5-29 Independent t-test results for alpha angle size by cribra (absent or present), WPC

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	-1.442	86	0.153	-4.362	3.025	-10.376	1.652
Right side	-1.587	81	0.116	-5.266	3.318	-11.868	1.336

5.4. Cam morphology & non-metric traits

The alpha angle cut off to determine the presence of cam morphology has been much debated in the literature, therefore 3 different cut off points have been assessed, ≥50°, ≥55°, ≥60°. To determine if there was a difference in proportions of femora with and without non-metric traits and having cam morphology chi-squared tests of homogeneity or a fisher's exact tests (if expected count is <5) were performed pooled for sex, for males only and for females only. This was assessed for Poirier's facets and plaque, but not for cribra, as unlike the other traits there was no significant difference found for in alpha angle size between femora with and without cribra. For plaque, if a significant difference in proportions was identified post hoc analysis was performed by running multiple 2x2 fisher's exact tests with a Bonferroni correction (p < 0.008333).

Poirier's facets

≥50° Threshold

When pooled for sex (Table 5-30), for the right side all femora with Poirier's facets present had an alpha angle ≥50°. There was a statistically significant difference in proportions of femora with an alpha angle ≥50° and those with an angle <50° dependent on the presence or absence of Poirier's facets, *p = 0.004.* The left side also showed the same pattern. For femora with Poirier's facets present, more had an alpha angle ≥50° than <50°. While those absent for Poirier's facet had a higher proportion with an alpha angle <50°. Again, a fisher's exact showed this difference in proportions was statistically significant, *p = 0.010.*

Table 5-30 Proportions of femora with/without cam morphology (50° threshold) by Poirier's facets, pooled sex, WPC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<50°)	56.6% (43)	0.0% (0)	51.8% (43)
	Present (≥50˚)	43.4% (33)	100.0% (7)	48.2%(40)
	Total	100.0% (76)	100.0% (7)	100.0% (83)
Left	Absent (<50°)	59.5% (47)	11.1% (1)	54.5% (48)
	Present (≥50˚)	40.5% (32)	88.9% (8)	45.5% (40)
	Total	100.0% (79)	100.0% (9)	100.0% (88)

For males only (Table 5-31), on the right side there was a significant difference in the proportions of femora with an alpha angle ≥50° and those with an angle of <50° between femora with and without Poirier's facets, *p = 0.035.* The left side also showed a significant difference in proportions *p = 0.015.*

Table 5-31 Proportions of femora with/without cam morphology (50° threshold) by Poirier's facets, males only, WPC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<50°)	44.4% (20)	0.0% (0)	38.5% (20)
	Present (≥50˚)	55.6% (25)	100.0% (7)	61.5% (32)
	Total	100.0% (45)	100.0% (7)	100.0% (52)
Left	Absent (<50°)	50.0% (25)	0.0% (0)	43.9% (25)
	Present (≥50˚)	50.0% (25)	100.0% (7)	56.1% (32)
	Total	100.0% (50)	100.0% (7)	100.0% (57)

For females (Table 5-32), there was no Poirier's facets present on the right side therefore it was not possible to carry out statistical analysis. While for the left side there was only two femora with Poirier's facet present.

Table 5-32 Proportions of femora with/without cam morphology (50° threshold) by Poirier's facets, females only, WPC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<50°)	72.4% (21)	0.0% (0)	72.5% (21)
	Present (≥50˚)	27.6% (8)	0.0% (0)	27.6% (8)
	Total	100.0% (29)	0.0% (0)	100.0% (29)
Left	Absent (<50°)	74.1% (20)	50.0% (1)	72.4% (21)
	Present (≥50˚)	25.9% (7)	50.0%(1)	27.6% (8)
	Total	100.0% (27)	100.0% (2)	100.0% (29)

≥55˚ Threshold

At the 55° threshold, when pooled for sex (Table 5-33), all right femora with Poirier's facets present had an alpha angle size ≥55°. While only 30.3% of femora without Poirier's facets present had an alpha angle size ≥55°. There was a statistically significant difference in proportions of femora with an alpha angle ≥55° and those with an angle <55° between those with and without Poirier's facets, p = *<0.0005.* For the left side, there was again a significant difference in proportions, $p = 0.002$.

Table 5-33 Proportions of femora with/without cam morphology (55° threshold) by Poirier's facets, pooled sex, WPC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<55°)	69.7% (53)	0.0% (0)	63.9% (53)
	Present (≥55˚)	30.3% (23)	100.0% (7)	36.1% (30)
	Total	100.0% (76)	100.0% (7)	100.0% (83)
Left	Absent (<55°)	67.1% (53)	11.1% (1)	61.4% (54)
	Present (≥55˚)	32.9% (26)	88.9% (8)	38.6% (34)
	Total	100.0% (79)	100.0% (9)	100.0% (88)

For males, on both sides 100% of femora with Poirier's facets present had cam morphology present (see Table 5-34). While for those without Poirier's facets there was a higher proportion without than with cam morphology present. On the both sides, this difference in proportions was significant, right side $p = 0.004$, left side $p = 0.004$.

Table 5-34 Proportions of femora with/without cam morphology (55° threshold) by Poirier's facets, males only, WPC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<55°)	60.0% (27)	0.0% (0)	51.9% (27)
	Present (≥55˚)	40.0% (18)	100.0% (7)	48.1% (25)
	Total	100.0% (45)	100.0% (7)	100.0% (52)
Left	Absent (<55°)	58.0% (29)	0.0% (0)	50.9% (29)
	Present (≥55˚)	42.0% (21)	100.0% (7)	49.1% (28)
	Total	100.0% (50)	100.0% (7)	100.0% (57)

If was not possible to run statistical analysis on females only as there was no femur with Poirier's facets present with an alpha angle ≥55° for either side.

≥60° Threshold

When pooled for sex (Table 5-35), on both sides, when Poirier's facets were present there was a higher proportion of femora with cam morphology present than absent. While, when the femora were absent for Poirier's facets there was a higher proportion without cam morphology present than with. This difference was significant for both the right, $p = 0.008$ and left sides, $p = <0.0005$.

Table 5-35 Proportions of femora with/without cam morphology (60° threshold) by Poirier's facets, pooled sex, WPC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<60°)	80.3% (61)	28.6% (2)	75.9% (63)
	Present (≥60˚)	19.7% (15)	71.4% (5)	24.1% (20)
	Total	100.0% (76)	100.0% (7)	100.0% (83)
Left	Absent (<60°)	75.9% (60)	11.1% (1)	69.3% (61)
	Present (≥60˚)	24.1% (19)	88.9% (8)	30.7% (27)
	Total	100.0% (79)	100.0% (9)	100.0% (88)

This same trend was seen when analysing for males only, with a significant difference in proportions on both the right, $p = 0.031$ and left sides, $p = 0.001$, see Table 5-36 below.

Table 5-36 Proportions of femora with/without cam morphology (60° threshold) by Poirier's facets, males only, WPC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<60°)	73.3% (33)	28.6% (2)	67.3% (35)
	Present (≥60˚)	26.7% (12)	71.4% (5)	32.7% (17)
	Total	100.0% (45)	100.0% (7)	100.0% (52)
Left	Absent (<60°)	70.0% (35)	0.0% (0)	61.4% (35)
	Present (≥60˚)	30.0% (15)	100.0% (7)	38.6% (22)
	Total	100.0% (50)	100.0% (7)	100.0% (57)

Plaque

≥50° Threshold

For the right side, only the absent and type C plaque groups had more femora with alpha angle <50° than ≥50°, see Table 5-37. The difference in proportions of femora with an alpha angle ≥50° and those with an angle <50˚ between femora with plaque, by type and without plaque, was statistically significant, *p = 0.005.* Post hoc showed this significant difference was between absent and type A, type A and type C (see Table 5-38 below). For the left side, only those absent for plaque and with type C plaque present had a greater proportion of alpha angles <50° than ≥50°. The difference in proportions can be seen in table 5-37 below. This difference was statistically significant, *p = 0.041.* Post hoc analysis showed this difference in proportions was between; absent and type A, type A and type C plaque groups, as shown in Table 5-38.

Table 5-37 Proportions of femora with/without cam morphology (50° threshold) by plaque group, pooled sex, WPC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<50°)	58.5%(31)	0.0%(0)	35.7%(5)	77.8%(7)	51.8%(43)
	Present (≥50˚)	41.5%(22)	100.0%(7)	64.3%(9)	22.2%(2)	48.2%(40)
	Total	100.0%(53)	100.0%(7)	100.0%(14)	100.0%(9)	100.0%(83)
Left	Absent (<50°)	60.0%(30)	30.8%(4)	41.2%(7)	87.5%(7)	54.5%(48)
	Present (≥50˚)	40.0%(20)	69.2%(9)	58.8%(10)	12.5%(1)	45.5%(40)
	Total	100.0%(50)	100.0%(13)	100.0%(17)	100.0%(8)	100.0%(88)

Table 5-38 Multiple fisher's exact analysis for cam morphology (50° threshold) between plaque groups, pooled sex, WPC

Pooled sex	Exact Sig. (2-sided)	
2 x 2 Fisher's Exact	Right side	Left side
Absent v Type A	0.001*	<0.0005*
Absent v Type B	0.054	0.034
Absent v Type C	0.082	0.119
Type A v Type B	0.042	0.558
Type A v Type C	<0.0005*	0.006*
Type B v Type C	0.008	0.014

For males, on the right side there was no significant difference in the proportions of femora with an alpha angle ≥50° and those with an angle <50˚ dependent on the presence or absence of plaque, *p = 0.166.* The left side also showed no significant difference in proportions, *p = 0.120.* See Table 5-39 for the proportions for both the left and right femora.

Table 5-39 Proportions of femora with/without cam morphology (50° threshold) by plaque group, males only, WPC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<50°)	40.6%(13)	0.0%(0)	44.4%(4)	60.0%(3)	38.5%(20)
	Present (≥50°)	59.4%(19)	100.0%(6)	55.6%(5)	40.0%(2)	61.5%(32)
	Total	100.0%(32)	100.0%(6)	100.0%(9)	100.0%(5)	100.0%(52)
Left	Absent (<50°)	48.0%(12)	25.0%(3)	35.7%(5)	83.3%(5)	43.9%(25)
	Present (≥50°)	52.0%(13)	75.0%(9)	64.3%(9)	16.7%(1)	56.1%(32)
	Total	100.0%(25)	100.0%(12)	100.0%(14)	100.0%(6)	100.0%(57)

For females, the small numbers meant statistical analysis was not possible, see Table 5-40.

Table 5-40 Proportions of femora with/without cam morphology (50° threshold) by plaque group, females only, WPC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<50°)	85.0%(17)	0.0% (0)	20.0% (1)	100.0%(3)	72.4%(21)
	Present (≥50°)	15.0% (3)	100.0%(1)	80.0%(4)	0.0%(0)	27.6%(8)
	Total	100.0%(20)	100.0% (1)	100.0%(5)	100.0%(3)	100.0%(29)
Left	Absent (<50°)	70.8%(17)	100.0%(1)	66.7%(2)	100.0%(1)	72.4%(21)
	Present (≥50°)	29.2%(7)	0.0%(0)	33.3%(1)	0.0%(0)	27.6%(8)
	Total	100.0%(24)	100.0%(1)	100.0%(3)	100.0%(1)	100.0%(29)

≥55° Threshold

The difference in the proportions of cam morphology within each plaque group can be seen in Table 5-41. For the right side there was a significant difference in proportions, *p = 0.008,* which post hoc analysis showed to be between absent and type A, type A and type C (Table 5-42). For the left side, there was no significant difference in proportions by plaque type, *p = 0.059.*

Table 5-41 Proportions of femora with/without cam morphology (55° threshold) by plaque group, pooled sex, WPC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<55°)	69.8%(37)	14.3%(1)	50.0%(7)	88.9%(8)	63.9%(53)
	Present (≥55°)	30.2%(16)	85.7%(6)	50.0%(7)	11.1%(1)	36.1%(30)
	Total	100.0%(53)	100.0%(7)	100.0%(14)	100.0%(9)	100.0%(83)
Left	Absent (<55°)	68.0%(34)	38.5%(5)	47.1%(8)	87.5%(7)	61.4%(54)
	Present (≥55°)	32.0%(16)	61.5%(8)	52.9%(9)	12.5%(1)	38.6%(34)
	Total	100.0%50	100.0%(13)	100.0%(17)	100.0%(8)	100.0%(88)

Table 5-42 Multiple fisher's exact analysis for cam morphology (55° threshold) between plaque groups, pooled sex, WPC

Pooled sex	Exact Sig. (2-sided)	
2 x 2 Fisher's Exact	Right side	Left side
Absent v Type A	0.008	N/A
Absent v Type B	0.210	N/A
Absent v Type C	0.423	N/A
Type A v Type B	0.174	N/A
Type A v Type C	0.009	N/A
Type B v Type C	0.086	N/A

For males, on the right side there was no significant difference in the proportions of femora with an alpha angle ≥55° and those with an angle <55° dependent on the presence, absence or type of plaque, *p = 0.215.* The left side also showed no significant difference in proportions *p = 0.212.* See Table 5-43 for the proportions of femora with and without cam morphology by plaque group for the left and right side.

Table 5-43 Proportions of femora with/without cam morphology (55° threshold) by plaque group, males only, WPC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<55°)	53.1%(17)	16.7%(1)	55.6%(5)	80.0%(4)	51.9%(27)
	Present (≥55°)	46.9%(15)	83.3%(5)	44.4%(4)	20.0%(1)	48.1%(25)
	Total	100.0%(32)	100.0%(6)	100.0%(9)	100.0%(5)	100.0%(52)
Left	Absent (<55°)	56.0%(14)	33.3%(4)	42.9%(6)	83.3%(5)	50.9%(29)
	Present (≥55°)	44.0%(11)	66.7%(8)	57.1%(8)	16.7%(1)	49.1%(28)
	Total	100.0%(25)	100.0%(12)	100.0%(14)	100.0%(6)	100.0%(57)

The data for females is presented in Table 5-44 below. Statistical analysis was not performed due to the small numbers per plaque category.

Table 5-44 Proportions of femora with/without cam morphology (55°threshold) by plaque group, females only, WPC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<55°)	95.0%(19)	0.0%(0)	40.0%(2)	100.0%(3)	82.8%(24)
	Present (≥55˚)	5.0%(1)	100.0%(1)	60.0%(3)	0.0%(0)	17.2%(5)
	Total	100.0%(20)	100.0%(1)	100.0%(5)	100.0%(3)	100.0%(29)
Left	Absent (<55°)	79.2%(19)	100.0%(1)	66.7%(2)	100.0%(1)	79.3%(23)
	Present (≥55˚)	20.8%(5)	0.0%(0)	33.3%(1)	0.0%(0)	20.7%(6)
	Total	100.0%(24)	100.0%(1)	100.0%(3)	100.0%(1)	100.0%(29)

≥60° Threshold

For the right side, all categories have more femora with an alpha angle <60° than ≥60°, see Table 5-45. The difference in proportions was statistically significant, $p = 0.022$. Post hoc analysis did not show this significance to be between any of the plaque categories (see Table 5-46). For the left side, more femora had alpha angle of <60˚ than ≥60˚ for all categories apart from type A plaque, see Table 5-45. The difference in proportions was not statistically significant, $p = 0.172$.

Table 5-45 Proportions of femora with/without cam morphology (60° threshold) by plaque group, pooled sex, WPC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<60°)	81.1%(43)	28.6%(2)	71.4%(10)	88.9%(8)	75.9%(63)
	Present (≥60°)	18.9%(10)	71.4%(5)	28.6%(4)	11.1%(1)	24.1%(20)
	Total	100.0%(53)	100.0%(7)	100.0%(14)	100.0%(9)	100.0%(83)
Left	Absent (<60°)	74.0%(37)	46.2%(6)	64.7%(11)	87.5%(7)	69.3%(61)
	Present (≥60°)	26.0%(13)	53.8%(7)	35.3%(6)	12.5%(1)	30.7%(27)
	Total	100.0%(50)	100.0%(13)	100.0%(17)	100.0%(8)	100.0%(88)

Table 5-46 Multiple fisher's exact analysis for cam morphology (60° threshold) between plaque groups, pooled sex, WPC

Pooled sex	Exact Sig. (2-sided)	
2 x 2 Fisher's Exact	Right side	Left side
Absent v Type A	0.008	N/A
Absent v Type B	0.468	N/A
Absent v Type C	1.000	N/A
Type A v Type B	0.159	N/A
Type A v Type C	0.035	N/A
Type B v Type C	0.611	N/A

For males, on both the right (*p = 0.301)* and left side (*p = 0.378)* there was no significant difference in the proportions of femora with and without cam morphology between any of the plaque groups (see Table 5-47).

Table 5-47 Proportions of femora with/without cam morphology (60° threshold) by plaque group, males only, WPC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<60°)	68.8%(22)	33.3%(2)	77.8%(7)	80.0%(4)	67.3%(35)
	Present (≥60°)	31.3%(10)	66.7%(4)	22.2%(2)	20.0%(1)	32.7%(17)
	Total	100.0%(32)	100.0%(6)	100.0%(9)	100.0%(5)	100.0%(52)
Left	Absent (<60°)	64.0%(16)	41.7%(5)	64.3%(9)	83.3%(5)	61.4%(35)
	Present (≥60°)	36.0%(9)	58.3%(7)	35.7%(5)	16.7%(1)	38.6%(22)
	Total	100.0%(25)	100.0%(12)	100.0%(14)	100.0%(6)	100.0%(57)

For females, the distribution of femora with and without cam morphology by plaque type is shown in Table 5-48 below. The small numbers per category meant statistical analysis was not performed.

Table 5-48 Distribution of femora with/without cam morphology (60° threshold) by plaque group, females only

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<60°)	100.0%(20)	0.0%(0)	60.0%(3)	100.0%(3)	89.7%(26)
	Present (≥60°)	0.0%(0)	100.0%(1)	40.0%(2)	0.0%(0)	10.3%(3)
	Total	100.0%(20)	100.0%(1)	100.0%(5)	100.0%(3)	100.0%(29)
Left	Absent (<60°)	83.3%(20)	100.0%(1)	66.7%(2)	100.0%(1)	82.8%(24)
	Present (≥60°)	16.7%(4)	0.0%(0)	33.3%(1)	0.0%(0)	17.2%(5)
	Total	100.0%(24)	100.0%(1)	100.0%(3)	100.0%(1)	100.0%(29)

5.5. Cam morphology & side asymmetry

There was no significant difference in the proportions of femora with cam morphology present (based on 50°, 55° and 60° thresholds) between the left and right sides (Table 5-49). The initial tests were pooled for sex and then split into males and females. There was no significant different in proportions of cam morphology for any threshold.

Table 5-49 McNemar's statistical test results for the differences in proportions of femora by cam morphology by sex, WPC

Sex	n	P-value		
		≥50°	≥55°	≥60°
Pooled sex	66	0.791	0.267	0.065
Males only	46	0.754	0.549	0.109
Females only	19	1.000	0.500	1.000

5.6. Cam morphology & sex

To determine if there was a significant difference in the proportion of femora with cam morphology present between males and females, chi-squared tests of homogeneity were run for each alpha angle threshold.

≥50° Threshold

At the 50° threshold, both sides showed a significant difference in proportions between the sexes (right side, $p = 0.03$, left side, $p = 0.012$). Males had more femora (for the right 62.3% and 55.0% for the left) with an alpha angle ≥50° than <50°, while females had more femora (72.4% on the right and left) with an alpha angle <50° than ≥50°, see

Table 5-50.

Table 5-50 Distribution of femora with/without cam morphology (50° threshold) by sex, WPC

Side	Cam morphology	Sex % (n)		Total
		Males	Females	
Right	Absent (<50°)	37.5%(20)	72.4%(21)	50.0%(41)
	Present (≥50˚)	62.3%(33)	27.6%(8)	50.0%(41)
	Total	100.0%(53)	100.0%(29)	100.0%982)
Left	Absent (<50°)	44.1%(26)	72.4%(21)	53.4%(47)
	Present (≥50˚)	55.9%(33)	27.6%(8)	46.6%(41)
	Total	100.0%(59)	100.0%(29)	100.0%(88)

≥55° Threshold

At the 55° threshold there was again a statistically significant difference in proportions of femora with and without cam morphology between males and females, see Table 5-51. For the right side, 47.2% of males and only 17.2% of females had an alpha angle ≥55°, $p = 0.007$. For the left side, again more male femora than female femora had cam morphology present at 49.2% and 20.7% respectively, $p = 0.010$.

Table 5-51 Distribution of femora with/without cam morphology (55° threshold) by sex, WPC

Side	Cam morphology	Sex % (n)		Total
		Males	Females	
Right	Absent (<55°)	52.8%(28)	82.8%(24)	63.4%(52)
	Present (≥55°)	47.2%(25)	17.2%(5)	36.6%(30)
	Total	100.0%(53)	100.0%(29)	100.0%(82)
Left	Absent (<55°)	50.8%(30)	79.3%(23)	60.2%(53)
	Present (≥55°)	49.2%(29)	20.7%(6)	39.8%(35)
	Total	100.0%(59)	100.0%(29)	100.0%(88)

≥60° Threshold

For the 60° threshold, both the right and left side showed a statistically significant difference in the proportions of femora with a cam morphology between males and females, see Table 5-52. For the right side, 32.1% of males while only 10.3% of females had an alpha angle ≥60°, $p = 0.028$. For the left side, again more male femora had an alpha angle ≥60° than females, 39.0% and 17.2% respectively. This difference was statistically significant, $p = 0.040$.

Table 5-52 Distribution of femora with/without cam morphology (60° threshold) by sex, WPC

Side	Cam morphology	Sex % (n)		Total
		Males	Females	
Right	Absent (<60°)	67.9%(36)	89.7%(26)	75.6%(62)
	Present (≥60°)	32.1%(17)	10.3%(3)	24.4%(20)
	Total	100.0%(53)	100.0%(29)	100.0%(82)
Left	Absent (<60°)	61.0%(36)	82.8%(24)	68.2%(60)
	Present (≥60°)	39.0%(23)	17.2%(5)	31.8%(28)
	Total	100.0%(59)	100.0%(29)	100.0%(88)

Chapter 6. Results II: Luís Lopes Collection (LLC)

In this chapter the results of the statistical analysis of the LLC sample will be presented. Descriptive statistics will be provided for each sample under statistical analysis. Not all femur could be used for all tests and therefore the number used will be presented each time.

Sections 6.1. and 6.2. provide an overview of the alpha angle data and non-metric traits for this sample and to determine if any additional factors are acting on these measurements, such as:

- Side
- Age (continuous scale)
- Age range category
- Offset ratio

Section 6.3. focuses on determining if there is a significant difference in alpha angle size dependent on the presence/absence of the non-metric traits; Poirier's facets, plaque and cribra. This will also be controlled by various factors including:

- Offset ratio
- Age range category
- Age (continuous scale)

The results in section 6.4. show the difference in proportions of femora with and without cam morphology (using three commonly used alpha angle thresholds from the literature ≥50°, ≥55°, ≥60°) by the presence of non-metric traits.

Section 6.5. presents the results determining if there is side asymmetry of cam morphology.

Section 6.6. is focused determining if occupational activity has an impact on the presence of non-metric traits and alpha angle size.

6.1. Alpha angle information

Alpha angle size by side

The average alpha angle for the whole sample of observable femora (n=207) was 54.18°. The mean alpha angle for the left femora (n=105) was 54.70° and 53.64° for the right (n=102). Table 6-1 shows the descriptive statistics for alpha angle size when pooled for side, left side only and right side only and Figure 6-1 shows the distribution of alpha angles for each side.

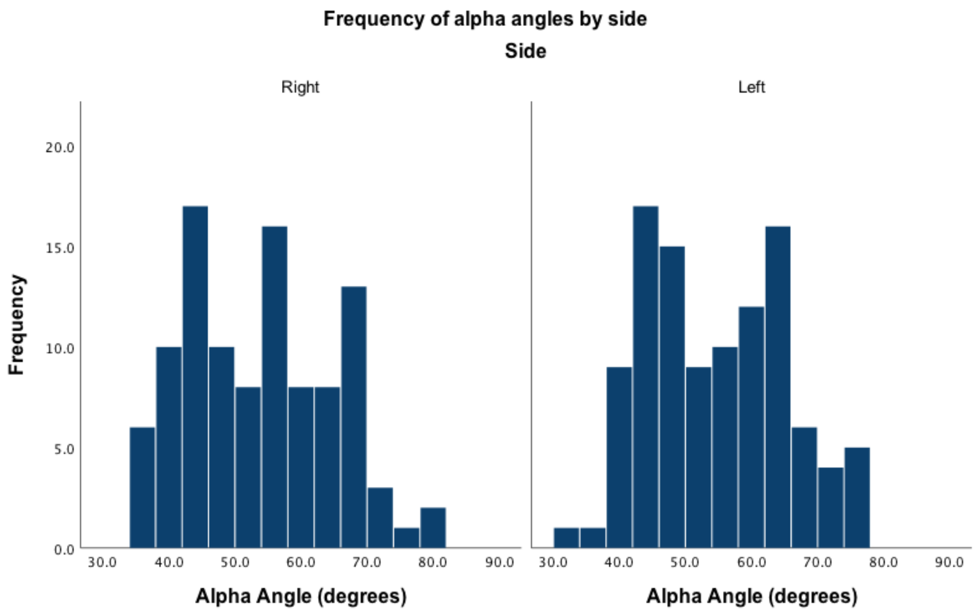


Figure 6-1 Histogram of distribution of alpha angles by side, LLC

Table 6-1 Alpha angle descriptive statistics for all femora, left femora only and right femora only, LLC

Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
All femora	207	46.49	33.63	80.12	54.18	10.99
Left Femora	105	43.34	33.63	76.97	54.70	10.69
Right Femora	102	45.97	34.15	80.12	53.64	11.32

Bilateral asymmetry of mean alpha angle size was determined using a paired sample t-test. Only individuals (n=99) with alpha angles recorded on both femora were included. The left femora (54.55° ± 10.88°) had a higher mean alpha angle than the right femora (53.70° ± 11.27°) (Table 6-2), this difference was not however statistically significantly, $t(98) = 0.889$, $p = 0.376$, $d = 0.09$, Table 6-3.

Table 6-2 Paired samples descriptive statistics for left and right femora alpha angles, LLC

Side	N	Mean (°)	Std. Dev	Std. Error Mean
Left	99	54.55	10.88	1.09
Right	99	53.70	11.27	1.13

Table 6-3 Paired sample t-test data table for mean alpha angle size by side, LLC

	Paired differences							
				95% confidence interval				
Alpha angles	Mean	Std. dev	Std. error mean	Lower	Upper	t	df	Sig. (2-tailed)
Left side– right side	0.851	9.518	0.957	-1.048	2.749	0.889	98	0.376

Alpha angle size by age

Unlike the Wharram Percy collection, the LLC had exact age data present, and therefore, it was possible to determine if there was a relationship between alpha angle size and age of the individual. When pooled for side there was a small, but not statistically significant correlation, between age and alpha angle size *r(207) = 0.120, p = 0.085,* Figure 6-2 shows a scatterplot of alpha angle against age. For the left side only, there was also a small but not statistically significant correlation between age and alpha angle size *r(105) = 0.171, p = 0.081.* While for the right side there was also a small but not statistically significant correlation between age and alpha angle size *r(102) = 0.066, p = 0.510.*

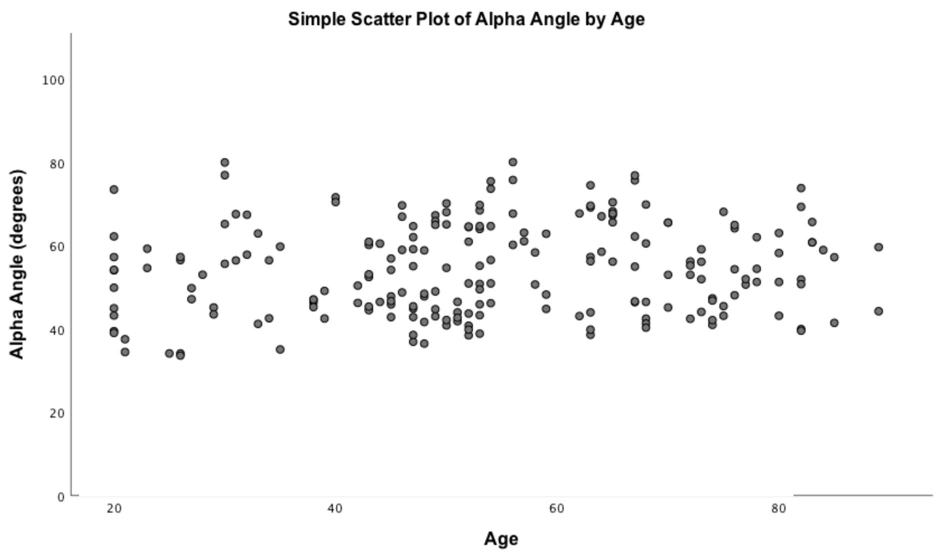


Figure 6-2 Scatterplot of angle angles by age, pooled for side, LLC

The age data was then split into categories, as with the Wharram Percy collection, to allow direct comparison. Figure 6-3 shows the number of individuals per age range category and the descriptive statistics for alpha angle size per age range category is shown in Table 6-4.

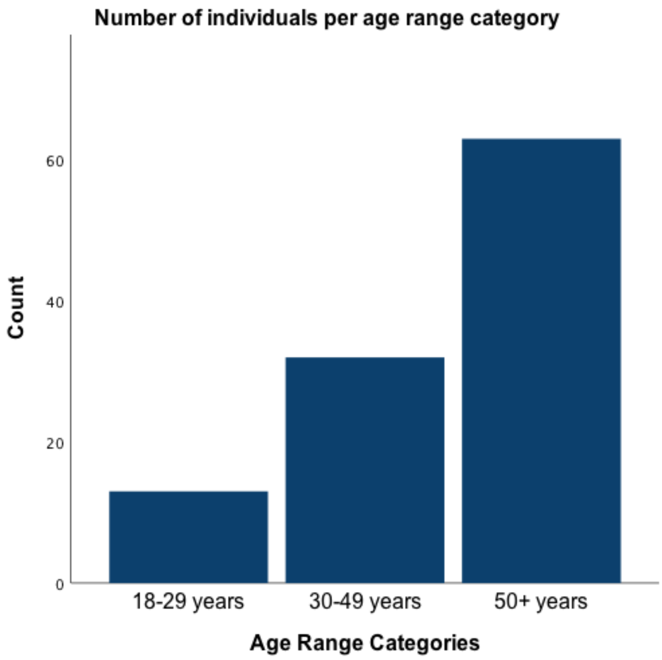


Figure 6-3 Bar chart of number of individuals per age range, LLC

Table 6-4 Number of individuals and femora per age category, LLC

Age Ranges	Number of males	Number of femora	Percentage of femora
18-29 years	13	26	12.0%
30-49 years	32	64	29.6%
50+ years	63	126	58.3%
Total	108	216	100.0%

One-way ANOVA for the right side showed there was an increase in alpha angle size with increase in age range category, from 18-29 years (47.73° ± 11.68°) to 30-49 years (53.78° ± 10.60°) to 50+ years (54.78° ± 11.44°). This difference was however not statistically significant, $F(2, 99) = 1.973$, $p = 0.145$, $\eta^2 = 0.038$. For the left side, the mean alpha angle size also increased from 18-29 years (48.84° ± 9.37°) to 30-49 years (53.42° ± 10.80°) to 50+ years (56.43° ± 10.54°). This difference was also not statistically significant, $F(2, 102) = 2.951$, $p = 0.057$, $\eta^2 = 0.055$. Table 6-5 shows the descriptive statistics for alpha angle size for each age range category.

Table 6-5 Alpha angle descriptive statistics per age category by femoral side, LLC

Age range	Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
18-29 years	Right	12	39.37	34.15	73.52	47.73	11.68
	Left	12	28.62	33.63	62.25	48.84	9.37
	All	24	39.89	33.63	73.52	48.28	10.37
30-49 years	Right	32	44.92	35.10	80.03	53.78	10.60
	Left	30	38.38	38.59	76.97	53.42	10.80
	All	62	44.92	35.10	80.03	53.60	10.61
50+ years	Right	58	41.63	38.49	80.12	54.78	11.44
	Left	63	37.32	39.59	76.91	56.43	10.54
	All	121	41.63	38.49	80.12	55.64	10.97

Alpha angles and offset ratios

In order to understand if femoral head concavity was associated with femoral head orientation in relation to the neck (anteriorly or posteriorly) a Spearman's correlation was run for both sides, Figure 6-4 and Figure 6-5 show scatterplots for alpha angle by offset ratio for both the right and left side respectively. On the right side there was a statistically significant weak correlation between alpha angle size and offset ratio, *rs(98) = -0.299, p = 0.003.*

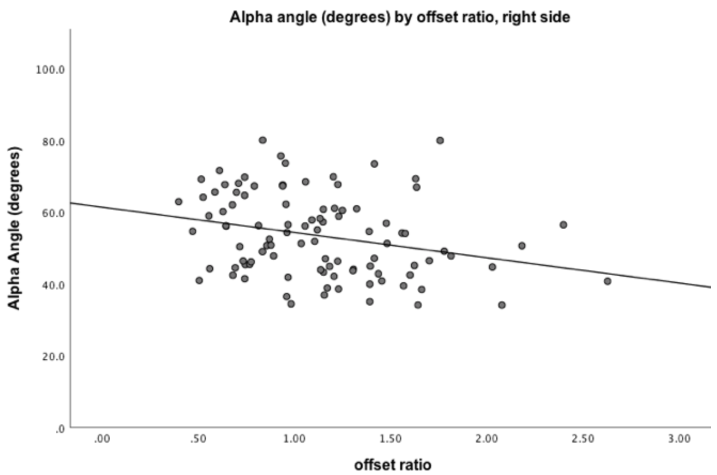


Figure 6-4 Scatterplot of alpha angle against offset ratio, right side only, LLC

For the left side there was also a statistically significant weak correlation between alpha angle size and offset ratio, *rs(100) = -0.335, p = 0.001.*

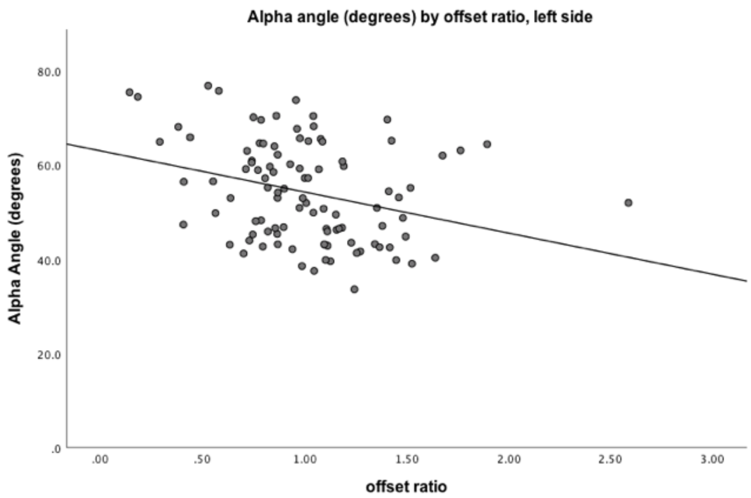


Figure 6-5 Scatterplot of alpha angle against offset ratio, left side only, LLC

6.2. Prevalence of non-metric traits

Poirier's facets

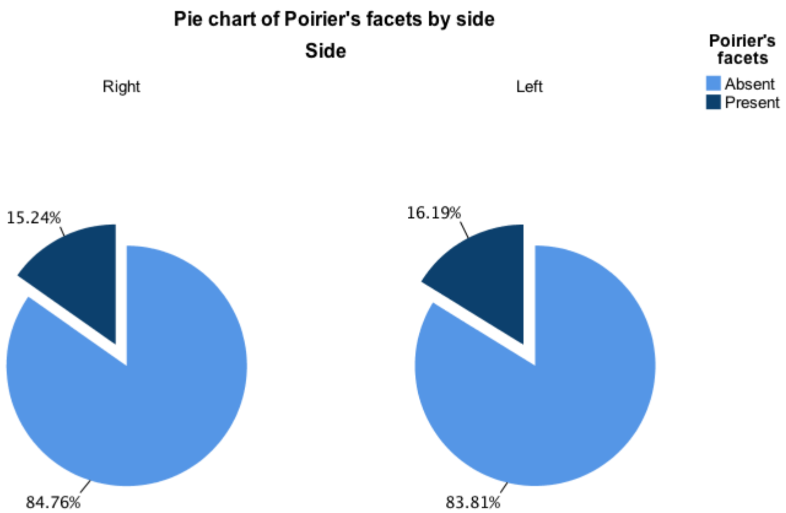


Figure 6-6 Pie charts of distribution of Poirier's facets in observable femora for left and right sides, LLC

Of the 216 femora analysed, Poirier's facets were present on 33 (15.71% of observable femora), absent on 177 (84.29% of observable femora) and unobservable due to post-mortem damage on 6 femora. For the left side, Poirier's facets were present on 17 femora (16.19% of observable left femora) and absent on 88 femora (83.81% of observable left femora). While for the right side, Poirier's facets were present on 16 femora (15.24% of observable right femora) and absent on 89 femora (84.76% of observable right femora), see Figure 6-6 and Table 6-6.

Table 6-6 Prevalence of Poirier's facets on the observable femora by side, LLC

Femora side	Total no. femur	No of femur unobservable for Poirier's facets	Observable femora					
			No of femur with Poirier's facets present	% of total femur with Poirier's facets	% for side with Poirier's facets	No of femur with Poirier's facets absent	% of total femur with Poirier's facets absent	% of side with Poirier's facets absent
Left	108	3	17	8.1%	16.5%	88	41.9%	83.8%
Right	108	3	16	7.6%	15.2%	89	42.4%	86.4%
Total	216	6	33	15.7%	15.7%	177	84.3%	84.3%

A total of 102 individuals (204 femora) had both femora present and analysed for the presence of Poirier's facets (Table 6-7). Of these, 82 (80.4%) individuals were absent for Poirier's facets on both femora, 13 (12.7%) individuals had bilateral Poirier's facets present, 4 (3.9%) individuals had Poirier's facets present on left but absent on right, 3 (2.9%) individuals had Poirier's facets present on right but absent on left.

Table 6-7 cross tabulation of the occurrence of Poirier's facets by left and right side, LLC

Poirier's facets		Right Side		
		Present	Absent	Total
Left Side	Present	13	4	17
	Absent	3	82	85
	Total	16	86	102

There was an increase in the number of Poirier's facets recorded with an increase in age category (see Table 6-8). For the 18-29 years category, only 2 femur had Poirier's facet recorded as present, 8 femora were recorded as having Poirier's facets present in the 30-49 years category and 23 were present for 50+ years categories. When considering percentages within each age range category Poirier's facets were present on 8.0% of observable femora in the 18-29 years group, 12.9% of the 30-49 years group and 18.7% within the 50+years age group (see Table 6-9).

Table 6-8 Count of femora categorised for presence or absence of Poirier's facets by age group, LLC

Age group	**Absent**	**Present**	**Unobservable**	**Total**
18-29 years	23	2	1	26
30-49 years	54	8	2	64
50+ years	100	23	3	126
Total	**177**	**33**	**6**	**216**

Table 6-9 Percentage of Poirier's facets for observable femora within and between age groups, LLC

Age group	% of observable femora absent for Poirier's facets within age group	% of observable femora present for Poirier's facets within age group	% of observable femora absent for Poirier's facets between age groups	% of observable femora present for Poirier's facets between age groups
18-29 years	92.0%	8.0%	13.0%	6.1%
30-49 years	87.1%	12.9%	30.5%	24.2%
50+ years	81.3%	18.7%	56.5%	69.7%

Due to the continuous nature of the age data for this sample an independent sample t-test was run to determine if there was a significant difference in mean age between individuals with Poirier's facets absent or present, the descriptive statistics are in Table 6-10. For the right side there was no significant difference *t(103)=-0.642, p= 0.522.* There was also no significant different for the left side, *t(103)=-1.065, p = 0.289,* (see Table 6-11).

Table 6-10 Descriptive statistics for age by Poirier's facets, LLC

Side	Poirier's facets	N	Mean (years)	Std. Dev	Std. Error Mean
Right	Absent	89	53.19	17.83	1.89
	Present	16	56.31	18.37	4.59
Left	Absent	88	52.88	18.38	1.96
	Present	17	58.00	16.93	4.11

Table 6-11 Independent t-test results for age (years) by the presence/absence of Poirier's facets, LLC

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	-1.065	103	0.289	-5.125	4.812	-14.669	4.419
Right side	-0.642	103	0.522	-3.121	4.863	-12.766	6.523

Plaque

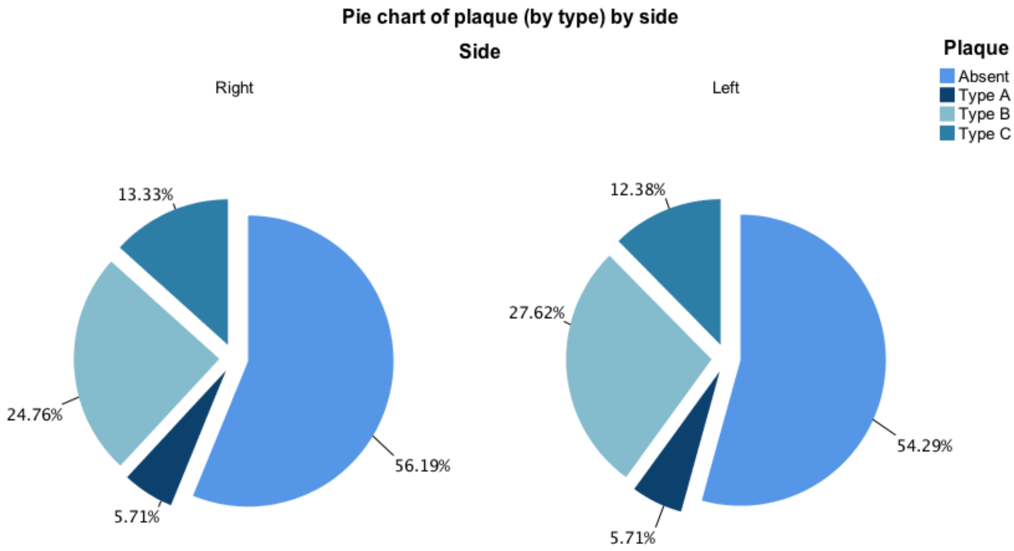


Figure 6-7 Pie charts of distribution of plaque by type recorded on observable femora for left and right side, LLC

Two hundred and sixteen femora were recorded for the presence of plaque as 6 were unobservable due to post mortem damage. Of the observable femora, plaque was present on 94 (45%) and absent on 116 (55%) femora. Twelve femora had type A (5.71%), 55 (26.19%) had type B and 27 (12.86%) had Type C. The prevalence rates of each form of plaque is shown in Table 6-12 and Figure 6-7.

Table 6-12 Prevalence of plaque by type on observable femora by side, LLC

Total			Observable femora											
			Type A			Type B			Type C			Absent		
Side	Total no. femur	N of unobserv femur	N	% of total	% for side	N	% of total	% for side	N	% of total	% for side	N	% of total	% for side
Left	108	3	6	2.86	5.71	29	13.81	27.62	13	6.19	12.38	57	27.14	54.29
Right	108	3	6	2.86	5.71	26	12.38	24.76	14	6.67	13.33	59	28.10	56.19
Total	216	6	12	5.71	5.71	55	26.19	26.19	27	12.86	12.86	116	55.24	55.24

N = number of femora

One hundred and two individuals had both femora present and observable for the presence of plaque. Table 6-13 shows the cross tabulation for the occurrence of plaque on the left side and right side. 46.08% (47/102) of individuals were recorded as no having plaque on either femora. Type A plaque occurred bilaterally in 3/102 individuals. Type B and C more commonly occurred bilaterally, 19/102 and 7/102 respectively.

Table 6-13 cross tabulation of the occurrence of plaque by left and right side, LLC

		Right side				
	Type	**A**	**B**	**C**	**Absent**	**Total**
Left side	**A**	3	2	0	1	6
	B	2	19	2	5	28
	C	0	1	7	4	12
	Absent	1	4	4	47	56
	Total	6	26	13	56	102

There was an increase in the prevalence of observable femora with plaque present from 18-29 years (12.0%) to 30-49 years (51.6%) to 50+ years (48.0%). For the 18-29 years, 30-49 years and 50+ years groups type B was the most prevalent form of plaque, 8.0%, 33.9% and 26.0% respectively (see Table 6-14, Table 6-15 and Table 6-16 for age range category data).

Table 6-14 Count of femora categorised for plaque type by age group, LLC

Age group	Absent	Type A	Type B	Type C	Unobservable	Total
18-29 years	22	1	2	0	1	26
30-49 years	30	5	21	6	2	64
50+ years	64	6	32	21	3	126
Total	**116**	**12**	**55**	**27**	**6**	**216**

Table 6-15 Percentage of femora within each age group category by plaque type, LLC

Age group	% of observable femora absent for Plaque within age group	% of observable femora present for Type A within age group	% of observable femora present for Type B within age group	% of observable femora present for Type C within age group
18-29 years	88.0%	4.0%	8.0%	0.0%
30-49 years	48.4%	8.1%	33.9%	9.7%
50+ years	52.0%	4.9%	26.0%	17.1%

Table 6-16 Percentage of femora within each plaque type group by age range category, LLC

Age group	**% of observable femora absent for Plaque between age group**	**% of observable femora present for Type A between age group**	**% of observable femora present for Type B between age group**	**% of observable femora present for Type C between age group**
18-29 years	19.0%	8.3%	3.6%	0.0%
30-49 years	25.9%	41.7%	38.2%	22.2%
50+ years	55.2%	50.0%	58.2%	77.8%

With regards to age and plaque, for the right side the age data for absent and type C plaque was not normally distributed (absent *p = 0.005, type C p = 0.003*) and it was not possible to transform the data for a comparison test. A Kruskall-Wallis H was therefore used which showed the median age was not significantly different between the plaque types, *H(3) = 1.117, p = 0.773.* For the left side, the age data was not normally distributed for the absent plaque group *(p = 0.006)* however as n >30 a one-way ANOVA was still run. There was no significant difference between the mean age and plaque type, Welch's *F(3, 19.771)= 2.243, p=0.115.* The descriptive statistics for age by plaque types is shown in Table 6-17.

Table 6-17 descriptive statistics for age by plaque type, LLC

Side	Plaque	N	Mean (years)	Std. Dev	Std. Error
Right	Absent	59	52.39	20.49	2.67
	Type A	6	56.50	15.39	6.28
	Type B	26	53.54	14.12	2.77
	Type C	14	58.07	13.10	3.50
Left	Absent	57	53.02	18.38	2.69
	Type A	6	43.17	16.93	6.74
	Type B	29	53.45	14.48	2.69
	Type C	13	62.15	13.93	3.86

Cribra

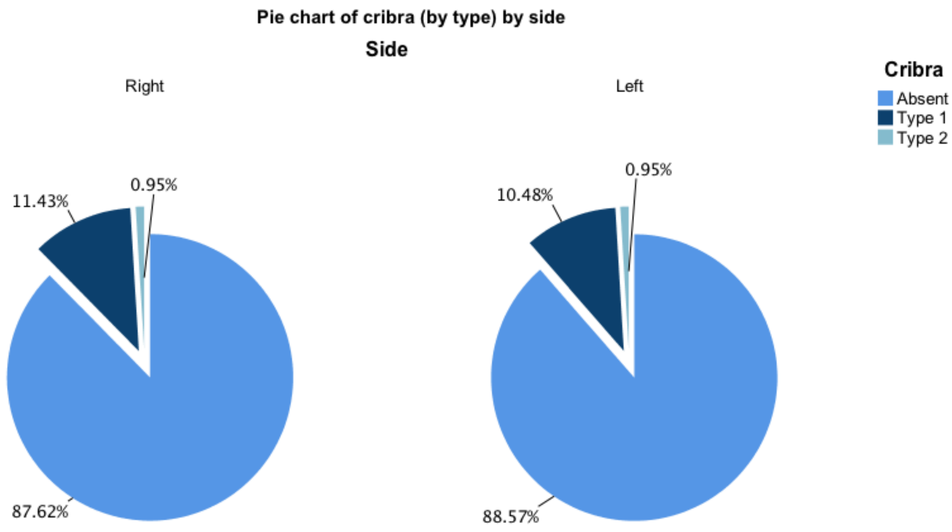


Figure 6-8 Pie charts of distribution of cribra by type recorded on observable femora for left and right side, LLC

Two hundred and four femora were recorded for the presence of cribra as 6 cases were unobservable due to post mortem damage. Of the observable femora, cribra was present on 25 and absent on 185. Of 25 femora with cribra 23 (92%) had type 1, 2 (8%) had type 2 present. Table 6-18 and Figure 6-8 show the prevalence rates of cribra.

Table 6-18 Prevalence of cribra on observable femora by side, LLC

Total			Observable								
			Type I			Type II			Absent		
Side	Total no. femur	N of unobserv femur	N	% of total	% for side	N	% of total	% for side	N	% of total	% for side
Left	108	3	11	5.24	10.48	1	0.48	0.95	93	44.29	88.57
Right	108	3	12	5.71	11.43	1	0.48	0.95	92	43.81	87.62
Total	216	6	23	10.95	10.95	2	0.95	0.95	185	88.10	88.10

N = number of femora

A total of 102 individuals (204 femora) had both femora present and analysed for the presence of cribra (Table 6-19). Of these 85 (83.33%) individuals were absent for cribra on both femora. Seven (6.86%) individuals had bilateral type I cribra and 1 (0.98%) individuals had bilateral type II cribra. Cribra is also more likely to present bilaterally than unilaterally in this sample.

Table 6-19 Cross tabulation of the occurrence of cribra by left and right side, LLC

	Type	Right side			
		I	II	Absent	Total
Left side	I	7	0	4	11
	II	0	1	0	1
	Absent	5	0	85	90
	Total	12	1	89	102

The prevalence of femora with cribra present was highest for the 18-29 years group n=10 (4.76% of observable femora) followed by the 30-49 years category n= 8 (3.81% of observable femora) then the 50+ years group n= 7 (3.33% of observable femora), see Table 6-20, 6-21 and 6-22 for further data on cribra by age range category.

Table 6-20 Count of femora categorised for cribra type by age group, LLC

Age group	Absent	Type I	Type II	Unobservable	Total
18-29 years	15	8	2	1	26
30-49 years	54	8	0	2	64
50+ years	116	7	0	3	126
Total	**185**	**23**	**2**	**6**	**216**

Table 6-21 Percentage of femora within each age range category by cribra (by type), pooled side, LLC

Age group	% of observable femora absent for cribra within age group	% of observable femora present for Type I within age group	% of observable femora present for Type II within age group
18-29 years	60.0%	32.0%	8.0%
30-49 years	87.1%	12.9%	0.0%
50+ years	94.3%	5.7%	0.0%

Table 6-22 Percentage of femora with/without cribra (by type) by age range category, pooled side, LLC

Age group	% of observable femora absent for cribra between age group	% of observable femora present for Type I between age group	% of observable femora present for Type II between age group
18-29 years	8.1%	34.8%	100.0%
30-49 years	29.2%	34.8%	0.0%
50+ years	62.7%	30.4%	0.0%

Cribra occurred more commonly in younger individuals, this was shown by independent sample t-tests (see Table 6-24). The descriptive statistics for age by cribra (absent or present) are shown in Table 6-23. On the right side, there was statistically significant difference in age between those with (42.69 ± 16.07 years) and without (55.22 ± 17.63 years) cribra present, *t(103)=2.422, p=0.017.* For the left side mean age was significantly lower for those with cribra (37.92 ± 16.35 years) when compared to those without (55.74 ± 17.46 years) cribra present, *t(103)=3.351, p=0.001.*

Table 6-23 Descriptive statistics for age by cribra, LLC

Side	Cribra	N	Mean (years)	Std. Dev	Std. Error Mean
Right	Absent	92	55.22	17.63	1.84
	Present	13	42.69	16.07	4.46
Left	Absent	93	55.74	17.46	1.81
	Present	12	37.92	16.35	4.72

Table 6-24 Independent t-test results for age (years) by the presence/absence of cribra, LLC

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	3.351	103	0.001	17.825	5.320	7.275	28.376
Right side	2.422	103	0.017	12.525	5.171	2.324	22.727

6.3. Alpha angles and non-metric traits

Statistical analysis was run to determine if there was a difference in mean alpha angle size between femora with and without non-metric traits present. In addition to this, analysis was run to establish if femoral head translation (through offset ratio) had an impact on this. As there was a difference in the proportion of femora with non-metric traits present between the age range categories, analysis was carried out to determine if there was an interaction effect between age and the presence of non-metric traits on alpha angle size.

Poirier's facets

The right side showed a significant difference in mean alpha angle size between femora with Poirier's facets present (68.57° ± 6.99°) compared to those without (50.92° ± 9.82°), *t(24.810) = 8.435, p = <0.0005.* The left side also showed a significant difference between those with Poirier's facets present (63.22° ± 8.90°) and those without (53.03° ± 10.31°), *t(102) = 3.802, p = <0.0005* when an independent sample t-test was used. The distribution of alpha angles for femora with and without Poirier's facets is shown in Figure 6-9. It clearly shows the pattern between the two groups. The descriptive statistics for alpha angle size between those with and without Poirier's facets are shown in Table 6-25.

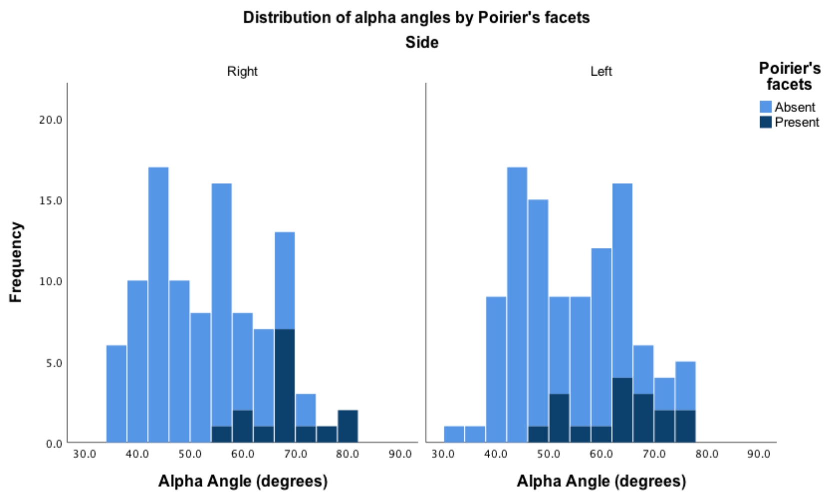


Figure 6-9 Histogram of distribution of alpha angles by the present of Poirier's facets, LLC

Table 6-25 Descriptive statistics for alpha angle size when split by femoral side and presence/absence of Poirier's facets, LLC

Side	Poirier's facets	N	Mean (°)	Min. (°)	Max. (°)	Range (°)	Std. Dev.
Left Femora	Absent	87	53.03	33.63	76.91	43.28	10.31
	Present	17	63.22	48.50	76.97	28.48	8.90
Right Femora	Absent	86	50.92	34.15	73.71	39.56	9.82
	Present	15	68.57	56.24	80.12	23.88	6.99

When one-way ANCOVAs were run to determine if there was still a statistically significant difference in alpha angle size between those with and without Poirier's facets while adjusting for offset ratio, there was still a significant difference on both sides. Figure 6-10 shows the pattern between alpha angle and offset ratio for those with and without Poirier's facets in the form of a scatterplot. For the right side, the alpha angle data was transformed, as the original data did not have homogeneity of regression slopes. After adjusting for offset ratio, there was a statistically significant difference in alpha angle size between femora with and without Poirier's facets, $F(1, 95) = 36.976, p < 0.0005$, partial $\eta^2 = 0.280$.

For the left side there was also a statistically significant difference in alpha angle size between femora with and without Poirier's facets when adjusted for offset ratio, $F(1, 96) = 10.168, p = 0.002$, partial $\eta^2 = 0.096$. The data for the standardized residuals for alpha angles was not normally distributed for the absent Poirier's facet group according to a Shapiro-Wilks test, $p = 0.002$ however it was not possible to transform the data to normality however the sample size was >30.

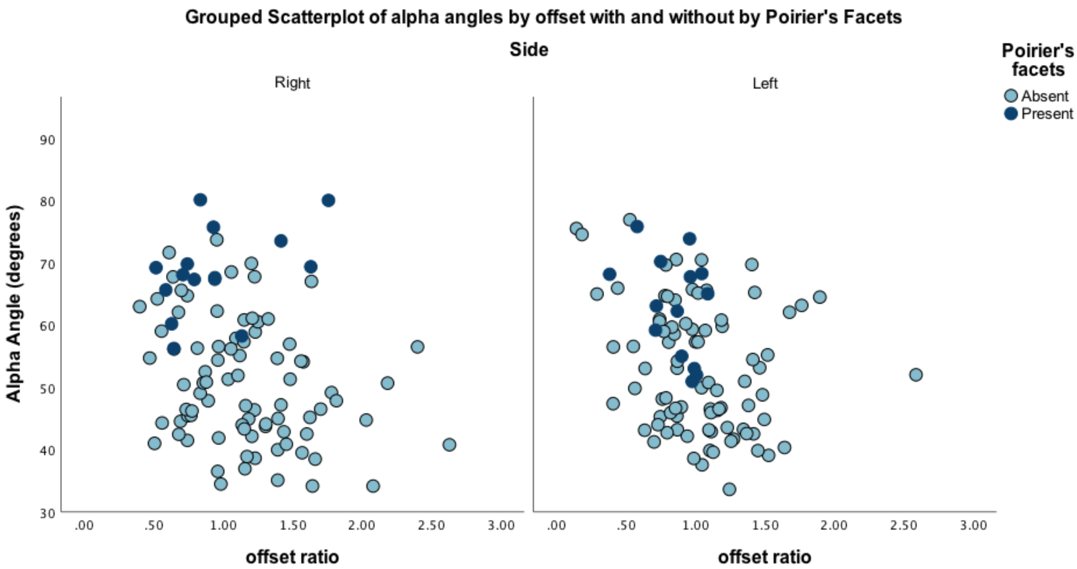


Figure 6-10 Grouped scatterplot of alpha angle size by offset ratio for femora with/without Poirier's facets, LLC

It was shown that age did not have a significant impact on alpha angle size when using exact age data, however, to compare directly to the Wharram Percy collection, and to determine if age range category had an impact on the mean alpha angle size between femora with or without Poirier's facets, two-way ANOVAS were run. For the right side, there was no statistically significant interaction between age range category and Poirier's facets on alpha angle size, $F(2,95) = 0.662, p = 0.518$, partial $\eta^2 = 0.014$. Main effect analysis showed there was a significant impact of Poirier's facets, $F(1,95) = 28.343, p = <0.0005$ but not age range category, $F(2,95) = 0.011, p = 0.989$ on alpha angle size. The residual data for alpha angles was however not normally distributed for those absent for Poirier's facets and in 50+ years category ($p = 0.003$). A comparison test using transformed was not however possible as the data would not transform to a normal distribution. The sample size was >30. There was also only one femur present in the group for Poirier's facets present and18-29 years which is likely to impact results.

For the left side there was also no statistically significant interaction between age range category and Poirier's facets on alpha angle size, $F(2,98)= 0.154,\ p= 0.858$, *partial* $\eta^2=0.003$. Main effect analysis showed there was a significant impact of Poirier's facets, $F(1,98)=7.634,\ p=0.007$ but not age range category, $F(2,98)= 0.421,\ p=0.658$ on alpha angle size. The residual data for alpha angles was not normally distributed for those absent for Poirier's facets and in the age groups 30-49 years ($p = 0.007$) and 50+ years ($p = 0.037$). It was not possible to correct for this violation of normality through data transformation. There was also only one femur present in the group from Poirier's facet present and 18-29 years, which should be considered when considering these results.

Plaque

The descriptive statistics for alpha angle size by plaque type are shown in Table 6-26 below and Figure 6-12 shows the distribution of alpha angles by plaque type. For the right side, there were 3 extreme outliers present in type C data group, as shown in Figure 6-11. A comparison test was run excluding these outliers. When a one-way ANOVA was run with the outliers included alpha angle size decreased from type A (57.86° ± 11.66°) to type B (55.42° ± 9.87°) to type C (46.20°± 9.08°). While those absent for plaque had a mean alpha angle size of 53.92° ± 11.93°. There was no statistically significant difference found between alpha angle size and plaque type $F(3,97) = 2.473,\ p = 0.066,\ \eta^2=0.071$.

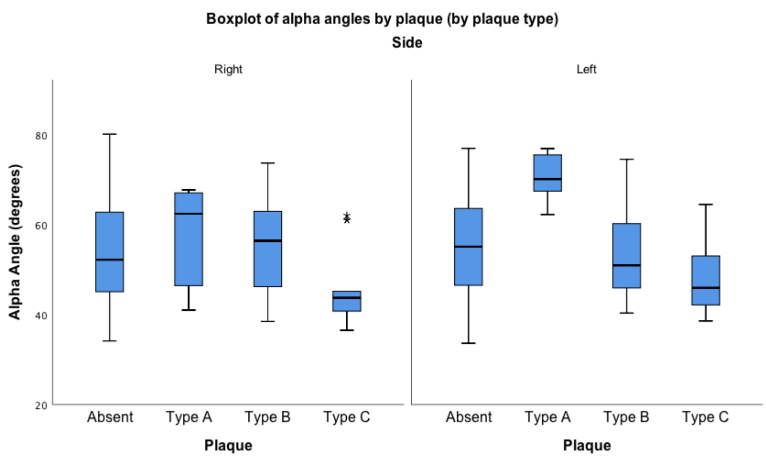


Figure 6-11 Boxplot of alpha angle size by plaque type, LLC

When the comparison test was run excluding the three extreme outliers the mean alpha angle size for type C plaque group was now 41.64° ± 3.15°. There was a statistically significant difference found between mean alpha angle size and plaque type, *Welch's* $F(3, 20.169) = 22.508$, $p = <0.0005$, $\eta^2=0.128$. The Games-Howell post hoc test found the statistical difference was between absent and type c ($p = <0.0005$) and type B and type C ($p = <0.0005$). There was however no reason to exclude these cases.

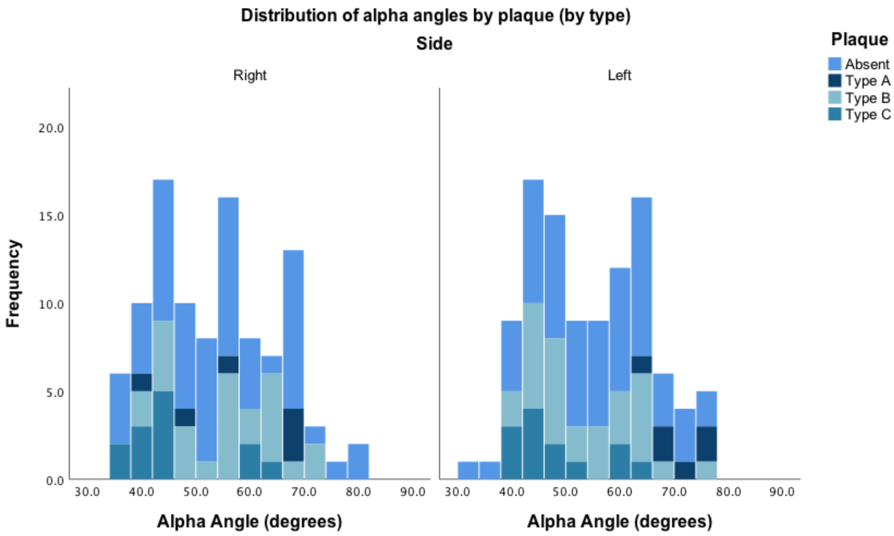


Figure 6-12 Histogram of distribution of alpha angles by the presence of plaque (by type), LLC

For the left side, there was also a decrease in mean alpha angle size from type A (70.39° ± 5.37°) to type B (53.65° ± 9.54°) to type C (48.14° ± 8.54°). The femora without plaque present had a mean alpha angle size of 55.08° ± 10.66°. A statistically significant difference was found in mean alpha angle size between plaque types, $F(3,100) = 7.058$, $p = <0.0005$, $\eta^2=0.175$. A Tukey-Kramer post hoc test showed significant difference was between type A and absent ($p = 0.003$), type A and type B ($p = 0.002$) and type A and type C ($p = <0.0005$).

Table 6-26 Descriptive statistics for alpha angle size when split by side and presence/absence of plaque, LLC

Plaque	Side	N	Mean (°)	Std. Dev.	Std. error	Min. (°)	Max. (°)
Absent	Left	56	55.08	10.67	1.42	33.63	76.97
	Right	56	53.92	11.93	1.59	34.15	80.12
	All	112	54.50	11.28	1.07	33.63	80.12
Type A	Left	6	70.39	5.37	2.19	62.25	76.91
	Right	6	57.86	11.66	4.76	41.01	67.74
	All	12	64.13	10.85	3.13	41.01	76.91
Type B	Left	29	53.65	9.54	1.77	40.35	74.55
	Right	26	55.42	9.87	1.93	38.49	73.71
	All	55	54.49	9.64	1.30	38.49	74.55
Type C	Left	13	48.14	8.54	2.37	38.59	64.48
	Right	13	46.20	9.08	2.52	36.51	62.07
	All	26	47.17	8.69	1.71	36.51	64.48

When controlling for offset ratio, via a one-way ANCOVA, for the right side there was no statistically significant difference in alpha angle size between femora with (by type) and without plaque, $F(3, 93)= 1.365, p=0.258$, *partial* $\eta^2=0.042$. For the left side after adjusting for offset ratio there was a statistically significant difference in alpha angle size between femora with (by type) and without plaque, $F(3, 94)= 6.100, p=0.001$, *partial* $\eta^2=0.163$. Figure 6-13 shows the right shows now clear pattern between offset ratio and alpha angle between plaque groups while on the left side a slight pattern is visible.

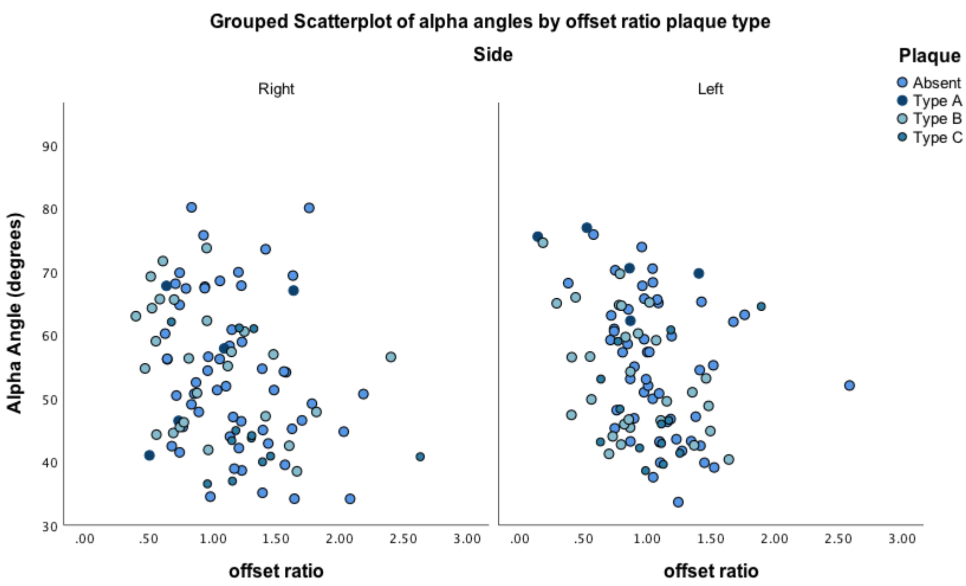


Figure 6-13 Grouped scatterplot of alpha angles by offset ratio for femora with/without plaque (by type), LLC

Due to the presence of exact age data it was possible to run one-way ANCOVAs, for the left and right side, to control for age when comparing the mean alpha angle size for femora with (by type) and without plaque. For the right side, when adjusted for age, there was not a significant difference in alpha angle size between femora with (by type) and without plaque $F(3, 96)= 2.517, p=0.063, \text{partial } \eta^2=0.073$. The standardized residual data for alpha angles for those with plaque type C present was not normally distributed ($p = 0.005$) and there were three extreme outliers for this plaque type. It was not possible to correct the violation of normality with the data transformation ($p = 0.048$) however it did transform the outliers to no longer be considered extreme. This comparison test did show a significant difference in alpha angle size between femora with (by type) and without plaque, $F(3,96)=2.885, p = 0.040, \text{partial } \eta^2 = 0.083.$

For the left side, the assumption of homogeneity of variances was violated however the data was normally distributed. The original data showed, when adjusted for age, there was a significant difference in alpha angle size between femora with (by type) and without plaque $F(3, 99)= 9.374, p <0.0005, \text{partial } \eta^2=0.221$. Due to the violation of the assumption of homogeneity of variances a comparison test was run with the alpha angle data transformed. Although the transformed data corrected for the homogeneity of variances it caused the standardized residual data for alpha angles and plaque type absent group to no longer be normally distributed ($p = 0.001$).

To compare directly to the Wharram Percy collection, and to determine if age range category had an impact on the mean alpha angle size between femora with (by type) or without plaque, two-way ANOVAS were run for each side separately. For the right side, there was no statistically significant interaction between age range category and plaque on alpha angle size, $F(4,91)= 0.289, p= 0.884, \text{partial } \eta^2=0.013.$ Main effect analysis showed there was no significant impact of plaque, $F(3,91)=2.638, p=0.054$ or age range category, $F(2,91)= 0.412, p=0.019$ on alpha angle size. There were however two extreme outliers present in the 50+ years group with plaque type C present and this data was also not normally distributed. A comparison test was run excluding these outliers which also showed no statistically significant interaction effect between plaque and age range category on alpha angle size $F(4,89)= 0.358, p= 0.838, \text{partial } \eta^2=0.016.$ However main effect analysis showed there was a significant impact of plaque, $F(3,89)=3.622$, $p=0.016$, partial $\eta^2=0.109$ but not age range category $F(2,89)=$, $p=0.363$, partial $\eta^2=0.023$ on alpha angle size.

For the left side, the original data did not meet the assumption of homogeneity of variances. A comparison test was therefore run to determine if this violation of assumption made a significant impact on the conclusions. For the original data there was no significant association between plaque type and age range category on alpha angle size $F(5, 93)=0.135$, $p=0.984$, partial $\eta^2=0.007$. Main effect analysis showed there was significant impact of plaque, $F(3,93)=7.786$, $p<0.0005$, partial $\eta^2=0.201$ but not age range category, $F(2,93)=3.046$, $p=0.052$, partial $\eta^2=0.061$ on alpha angle size. The comparison test, with transformed alpha angle data, also showed no significant association between plaque type and age range category on alpha angle size, $F(5, 93)=0.562$, $p=0.729$, partial $\eta^2=0.029$. Main effect analysis did however show there was a significant impact of both plaque, $F(3,93)=9.154$, $p<0.0005$, partial $\eta^2=0.228$ and age range category, $F(2,93)=4.950$, $p=0.009$, partial $\eta^2=0.096$ on alpha angle size. This transformation however meant the alpha angle residual data was not normally distributed for those in the 30-49 years and absent for plaque *($p = 0.002$).*

Cribra

The descriptive statistics for alpha angle size by cribra type are shown in Table 6-27 below and Figure 6-14 shows the distribution of alpha angles for each cribra type. Due to the presence of only two femora with type II plaque present, type I and II have been combined and independent sample t-tests have been run to determine if there was a significant difference in mean alpha angle size between femora with cribra and those without (see Table 6-28). For the right side, the mean alpha angle size was higher for femora absent for cribra (53.74° ± 11.17°) than for those with cribra (52.25° ± 12.79°). This difference was not statistically significant, $t(99) = 0.439$, $p = 0.661$.

For the left side, although the mean alpha angle size was again higher for the femora without cribra present (54.80° ± 10.89°) compared to those with cribra present (53.82° ± 9.86°) this was not statistically significant, $t(102) = 0.284$, $p = 0.777$.

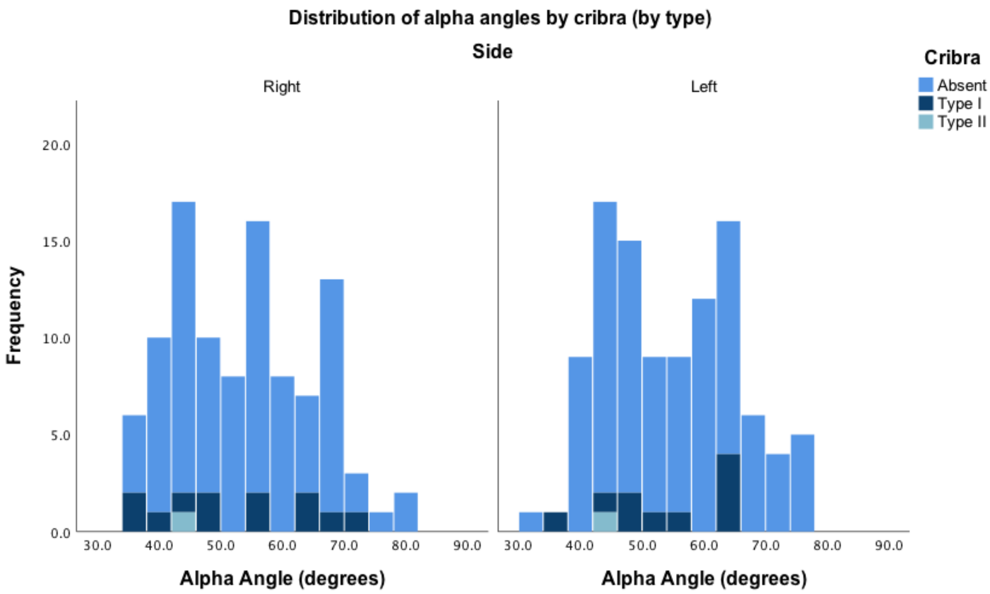


Figure 6-14 Histogram of distribution of alpha angles by the presence of cribra (by type), LLC

Table 6-27 Descriptive statistics of alpha angle size by the presence/absence or cribra, LLC

Plaque	Side	N	Mean (°)	Std. Dev.	Std. error	Min. (°)	Max. (°)
Absent	Left	93	54.80	10.89	1.13	33.63	76.97
	Right	88	53.74	11.17	1.19	34.16	80.12
	All	181	54.28	11.01	0.82	33.63	80.12
Type I & Type II total	Left	11	53.82	9.86	2.97	37.56	65.94
	Right	13	52.25	12.79	3.55	34.15	73.52
	All	24	52.97	11.32	2.31	34.15	73.52

Table 6-28 Independent sample t-test results for alpha angle size by presence/absence of cribra, for both left and right side, LLC

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	0.284	102	0.777	0.976	3.441	-5.850	7.802
Right side	0.439	99	0.661	1.486	3.382	-5.224	8.196

6.4. Cam morphology & non-metric traits

The presence of cam morphology is commonly determined using the alpha angle thresholds of ≥50°, ≥55° or ≥60°. This section shows the results of chi-squared and fisher's exact tests (if expected count is <5) to determine if there was a difference in proportions of femora with and without non-metric traits and having cam morphology. Analysis was not performed for cribra as no significant difference was found in alpha angle size between femora with and without cribra.

Poirier's facets

< / ≥ 50°

For the right side, all femora with Poirier's facets present had an alpha angle ≥50°. There was a statistically significant difference in the proportions of femora with an alpha angle ≥50° than those with an angle of <50°, dependent on the presence or absence of Poirier's facts, (*p= <0.0005).* The left side showed a similar pattern, with a greater proportion of femora with Poirier's facets present having an alpha angle ≥50° than <50°. Again, there was a statistically significant difference in proportions of femora, *p = 0.001.* Table 6-29 shows the proportion of femora with cam morphology absent or present for femora absent and present for Poirier's facets.

Table 6-29 Proportions of femora with/without cam morphology (50° threshold) by Poirier's facets, LLC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<50°)	50.0% (43)	0.0% (0)	42.6% (43)
	Present (≥50˚)	50.0% (43)	100.0% (15)	57.4% (58)
	Total	100.0% (86)	100.0% (15)	100.0% (101)
Left	Absent (<50°)	48.3% (42)	5.9% (1)	41.3% (43)
	Present (≥50˚)	51.7% (45)	94.1%(16)	58.7% (61)
	Total	100.0% (87)	100.0% (17)	100.0% (104)

< / ≥ 55°

For the right, all the femora with Poirier's facets present had an alpha angle ≥55°. There was again, a statistically significant difference in the proportions of femora with an alpha angle ≥55° than those with an angle of <55°, dependent on the presence or absence of Poirier's facts, $p= <0.0005$. The left side also showed a statistically significant difference in proportions of femora with an alpha angle <55° and ≥55° dependent on the presence or absence of Poirier's facts, $p = 0.01$. Table 6-30 shows the proportions of femora with and without cam morphology.

Table 6-30 Proportions of femora with/without cam morphology (55° threshold) by Poirier's facets, LLC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<55°)	65.1% (56)	0.0% (0)	55.4% (56)
	Present (≥55°)	34.9% (30)	100.0% (15)	44.6% (45)
	Total	100.0% (86)	100.0% (15)	100.0% (101)
Left	Absent (<55°)	57.5% (50)	23.5% (4)	51.9% (54)
	Present (≥55°)	42.5% (37)	76.5% (13)	48.1% (50)
	Total	100.0% (87)	100.0% (17)	100.0% (104)

< / ≥ 60°

For both sides a greater proportion of femora with Poirier's facets present had an alpha angle ≥60° (Table 6-31). While those without Poirier's facets present had a greater proportion without an alpha angle <60°. This was significant on the right $p <0.0005$ and left sides $p = 0.003$.

Table 6-31 Proportions of femora with/without cam morphology (60° threshold) by Poirier's facets, LLC

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<60°)	79.1% (68)	13.3% (2)	69.3% (70)
	Present (≥60°)	20.9% (18)	86.7% (13)	30.7% (31)
	Total	100.0% (86)	100.0% (15)	100.0% (101)
Left	Absent (<60°)	72.4% (63)	35.5%(6)	66.3% (69)
	Present (≥60°)	27.6% (24)	64.7% (11)	33.7% (35)
	Total	100.0% (87)	100.0% (17)	100.0% (104)

Plaque

To determine if there was a significant difference between plaque type and cam morphology, fisher's exact tests were run. When a significant difference was determined post hoc analysis, using pairwise comparisons via multiple Fisher's exact tests (2 x 2) with a Bonferroni correction (p = 0.008333) were used to determine between which groups is this significant difference in proportions. For the left side only 104 femora and for the right side only 101 femora were graded as either being absent for plaque or having type A, B or C plaque present.

< / ≥ 50°

With an alpha angle threshold value of 50° for the right side there were no significant differences in the proportions of femora with or with cam morphology present at each plaque category, *p = 0.059*. For the left side, there was however a significant difference, *p = 0.020*. Post hoc analysis showed only the comparison between type A & type C to be statistically significant, *p = 0.001* (see Table 6-33). The comparison showed 100% of femora with type A present had an alpha angle ≥ 50°, while there were more femora with type C plaque present without cam morphology (69.2%) (see Table 6-32).

Table 6-32 Proportions of femora with/without cam morphology (50° threshold) by plaque type, LLC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<50°)	39.3%(22)	33.3%(2)	34.6%(9)	76.9%(10)	42.6%(43)
	Present (≥50˚)	60.7%(34)	66.7%(4)	65.4%(17)	23.1%(3)	57.4%(58)
	Total	100.0%(56)	100.0%(6)	100.0%(26)	100.0%(13)	100.0%(101)
Left	Absent (<50°)	35.7%(20)	0.0%(0)	48.3%(14)	69.2%(9)	41.3%(43)
	Present (≥50˚)	64.3%(36)	100.0%(6)	51.7%(15)	30.8%(4)	58.7%(61)
	Total	100.0%(56)	100.0%(6)	100.0%(29)	100.0%(13)	100.0%(104)

Table 6-33 Multiple fisher's exact analysis for cam morphology (50° threshold) between plaque groups, LLC

Pooled sex	Exact Sig. (2-sided)	
2 x 2 Fisher’s Exact	Right side	Left side
Absent v Type A	NA	0.031
Absent v Type B	NA	1.000
Absent v Type C	NA	0.161
Type A v Type B	NA	0.079
Type A v Type C	NA	0.001*
Type B v Type C	NA	0.022

< / ≥ 55°

For the right side, there was no significant difference in the proportions of femora with and without cam morphology present between the plaque types, $p = 0.133$. For the left side there was a significant difference, $p = 0.011$. Post hoc analysis showed only the comparisons between type A and type C (p = <*0.0005*), and absent and type A ($p = 0.004$) to be significant different (see Table 6-35). Type A plaque was only present on femora with an alpha angle ≥55° group, while there were more femora with type C plaque (76.9%) present on femora without cam morphology. While there is a relatively equal split of femora with and without cam morphology for femora without plaque present (see Table 6-34).

Table 6-34 Proportions of femora with/without cam morphology (55° threshold) by plaque type, LLC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<55°)	58.9%(33)	33.3%(2)	42.3%(11)	76.9%(10)	55.4%(56)
	Present (≥55°)	41.1%(23)	66.7%(4)	57.7%(15)	23.1%(3)	44.6%(45)
	Total	100.0%(56)	100.0%(6)	100.0%(26)	100.0%(13)	100.0%(101)
Left	Absent (<55°)	48.2%(27)	0.0%(0)	58.6%(17)	76.9%(10)	51.9%(54)
	Present (≥55°)	51.8%(29)	100.0%(6)	41.4%(12)	23.1%(3)	48.1%(50)
	Total	100.0%(56)	100.0%(6)	100.0%(29)	100.0%(13)	100.0%(104)

Table 6-35 Multiple fisher's exact analysis for cam morphology (55° threshold) between plaque groups, LLC

Pooled sex	Exact Sig. (2-sided)	
2 x 2 Fisher's Exact	Right side	Left side
Absent v Type A	NA	0.004*
Absent v Type B	NA	0.841
Absent v Type C	NA	0.379
Type A v Type B	NA	0.028
Type A v Type C	NA	<0.0005*
Type B v Type C	NA	0.059

< / ≥ 60°

For the right side, there were no significant differences in the proportions, with and without cam morphology present between femora with type A, B or C or without plaque present, $p = 0.630$. For the left side, there was however a significant difference, $p = 0.003$. Post hoc analysis showed this difference was between type A & type B (p =

0.002), type A and type C (*p* = <*0.0005*) and type A and absent (*p* = <*0.0005*) (see Table 6-37). All femora with type A plaque present had an alpha angle size ≥60° as shown in Table 6-36. While the other forms of plaque had a greater proportion of femora with an alpha angle size <60°

Table 6-36 Proportions of femora with/without cam morphology (60° threshold) by plaque type, LLC

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<60°)	71.4%(40)	50.0%(3)	65.4%(17)	76.9%(10)	69.3%(70)
	Present (≥60˚)	28.6%(16)	50.0%(3)	34.6%(9)	23.1%(3)	30.7%(31)
	Total	100.0%(56)	100.0%(6)	100.0%(26)	100.0%(13)	100.0%(101)
Left	Absent (<60°)	66.1%(37)	0.0%(0)	72.4%(21)	84.6%(11)	66.3%(69)
	Present (≥60˚)	33.9%(19)	100.0%(6)	27.6%(8)	15.4%(2)	33.7%(35)
	Total	100.0%(56)	100.0%(6)	100.0%(29)	100.0%(13)	100.0%(104)

Table 6-37 Multiple fisher's exact analysis for cam morphology (60° threshold) between plaque groups, LLC

Pooled sex	Exact Sig. (2-sided)	
2 x 2 Fisher's Exact	Right side	Left side
Absent v Type A	NA	<0.0005*
Absent v Type B	NA	1.000
Absent v Type C	NA	0.065
Type A v Type B	NA	0.002*
Type A v Type C	NA	<0.0005*
Type B v Type C	NA	0.375

6.5. Cam morphology & side asymmetry

A McNemar's tests showed there was no significant difference in the proportions of cam morphology between sides at any threshold (Table 6-38) for this sample.

Table 6-38 McNemar's results for the differences in proportions of femora with cam morphology by side, LLC

	P-value		
n	≥50°	≥55°	≥60°
99	1.000	0.571	0.832

6.6. Occupation data

The occupation data present for the LLC meant it was possible to determine if there was a difference in alpha angle size between different occupations but also between occupational activity categories (as described in section 4.2.3.3). In this section, the distribution of age between each group will be analysed to determine if there is a significant difference between groups, which could impact the results for alpha angle analysis. The overall prevalence of non-metric traits between each occupational activity method will be presented. This will be followed by the analysis of alpha angle size data between occupational activity categories, by side and the presence of non-metric traits.

6.6.1. Distribution of age by occupational group

The distribution of age by ISCO-08 classification is shown in Table 6-39 below.

Table 6-39 Descriptive statistics of age by ISCO-08 occupation categories, LLC

Method	Categories	N	Min (years)	Max (years)	Mean (years)	Std. Dev
ISCO-08 Update	Armed Forces Occupations	8	47	89	69.50	15.64
	Managers/ Professionals	10	35	76	59.40	14.32
	Technicians & Associate Professionals	7	29	82	59.29	18.67
	Clerical support workers	12	25	67	47.00	14.32
	Services and sales workers	20	20	82	48.15	15.87
	Craft and related trades workers	35	20	83	52.03	19.42
	Elementary occupations	4	34	56	45.75	9.47
	Undetermined	12	20	85	62.08	18.947

The age distribution for method I is shown in table 6-40 below and Figure 6-15. For activity classification method I there was a greater number of individuals classified as having high activity followed by low activity then moderate activity. For all categories the minimum age was 20 years and the maximum age was >80 years. A one-way ANOVA showed no significant difference between groups, $F(2,85) = 0.006, p = 0.994, \eta^2=<0.0005$

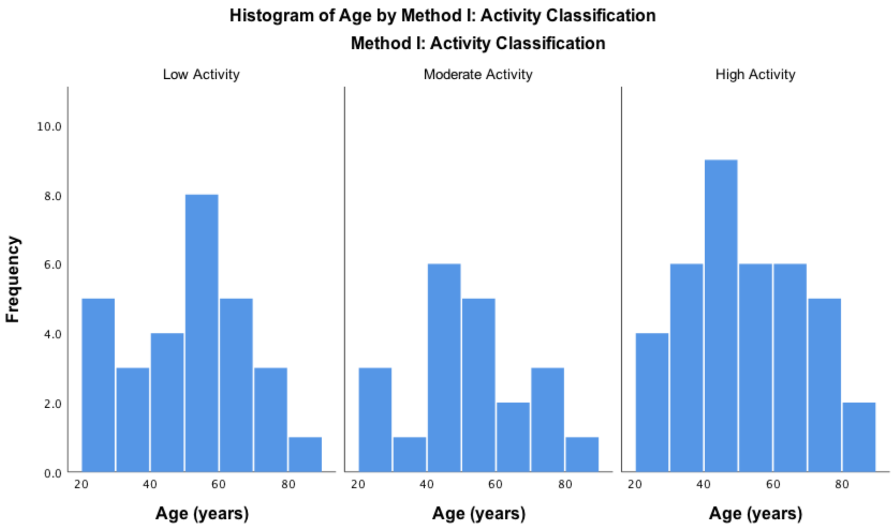


Figure 6-15 Histograms of age for Method I activity classification categories, LLC

Table 6-40 Descriptive statistics for age by activity category for method I, LLC

Method	Categories	N	Min (years)	Max (years)	Mean (years)	Std. Dev
Method I	Low Activity	29	20	82	50.97	17.01
	Moderate Activity	21	20	83	51.52	18.24
	High Activity	38	20	82	51.18	17.09

The age distribution for method II is shown in Table 6-41 below and Figure 6-16. For activity classification method II there was a greater number of individuals classified in the moderate intensity group followed light intensity then sedentary behaviour. A one-way ANOVA showed no significant difference in age between groups, $F(2,85) = 0.162$, $p = 0.851$, $\eta^2=0.004$.

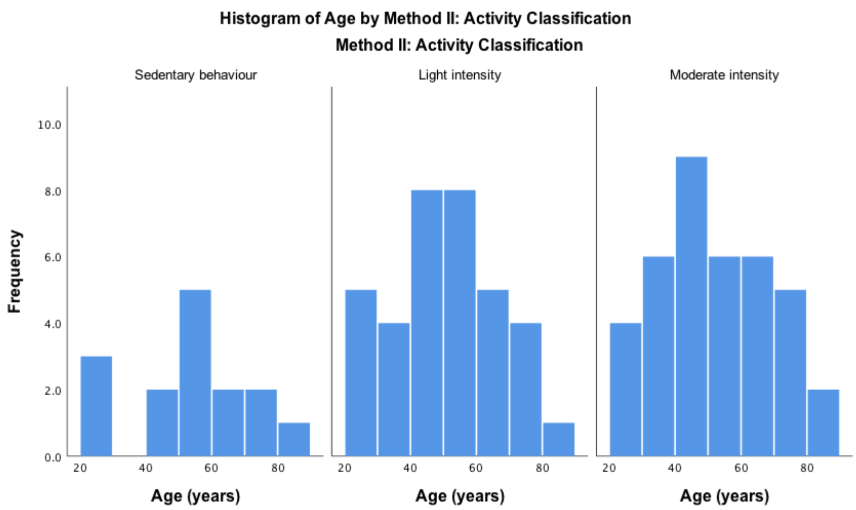


Figure 6-16 Histograms of age for Method II activity classification categories

Table 6-41 Descriptive statistics for age by activity category for method II, LLC

Method	Categories	N	Min (years)	Max (years)	Mean (years)	Std. Dev
Method II	Sedentary behaviour	15	25	82	53.33	18.28
	Light intensity	35	20	83	50.29	17.26
	Moderate intensity	38	20	82	51.18	17.09

Finally, for activity classification method III the age distribution is shown in Table 6-42 below and Figure 6-17. There was a greater number of individuals classified in the non-manual group than the manual group. An independent sample t-test showed no significant difference in age between groups, *t(94) = -0.345, p = 0.731*

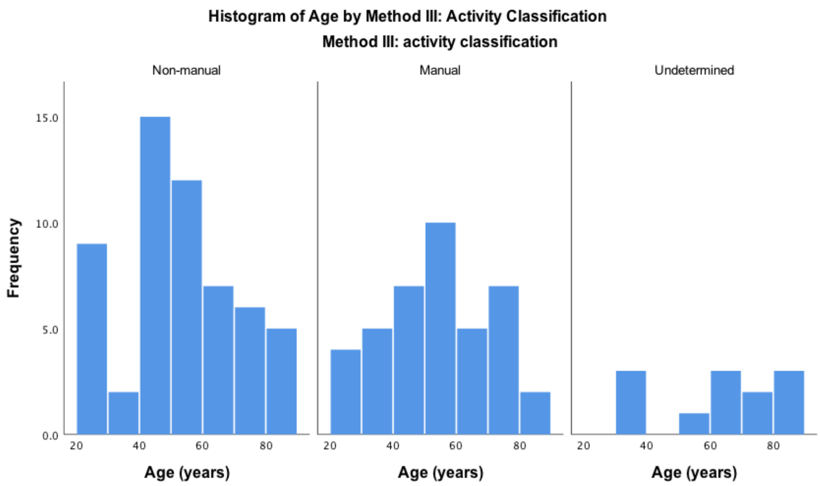


Figure 6-17 Histograms of age for Method III activity classification categories

Table 6-42 Descriptive statistics for age by activity category for method III, LLC

Method	Categories	N	Min (years)	Max (years)	Mean (years)	Std. Dev
Method III	Non-manual	56	20	85	52.16	18.08
	Manual	40	20	83	53.43	17.18
	Undetermined	12	30	89	62.33	19.68

6.6.2. Non-metric traits by occupational group

Poirier's facets

For method I (see Figure 6-18 & Table 6-43), there was an increase in percentage of Poirier's facets observed on femora for the left side from low activity to moderate activity to high activity groups. For the right side, there was a decrease from low activity to moderate activity (of one femur) and then an increase to high activity. When not divided by side, there is an overall increase from 8.6% at low activity to 14.3% for moderate activity and 22.4% at high activity in the prevalence of Poirier's facets.

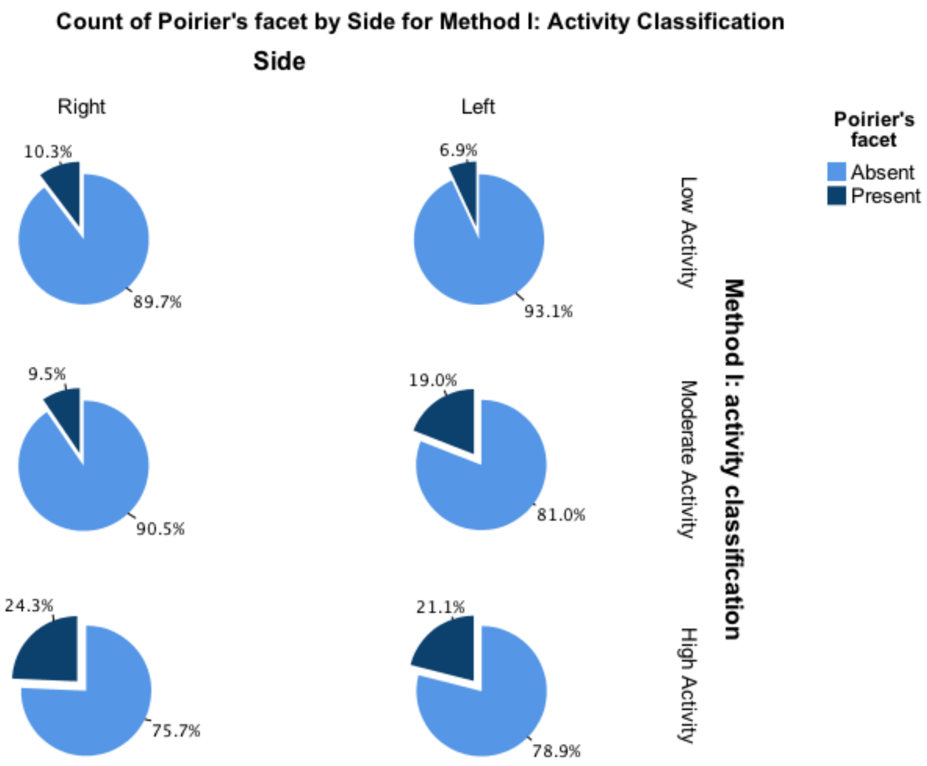


Figure 6-18 Pie charts of Poirier's facets by activity categories, method I, LLC

Table 6-43 Number of femora with & without Poirier's facets by occupational activity categories method I, LLC

Method	Categories	Side	N*	Poirier's facets	
				Absent	Present
Method I	Low Activity	Left	29	27	2
		Right	29	26	3
		Total	58	53	5
	Moderate Activity	Left	21	17	4
		Right	21	19	2
		Total	42	36	6
	High Activity	Left	38	30	8
		Right	37	28	9
		Total	76	58	17

*N = total number of observable femora

For method II (see Figure 6-19 and Table 6-44), there was an increase in percentage of Poirier's facets observed on femora for both sides from sedentary behaviour to light intensity to moderate intensity groups. When not divided by side there is an overall increase in the prevalence of Poirier's facets from 0.0% for sedentary behaviour, to 15.7% for light intensity, and 22.7% for moderate activity.

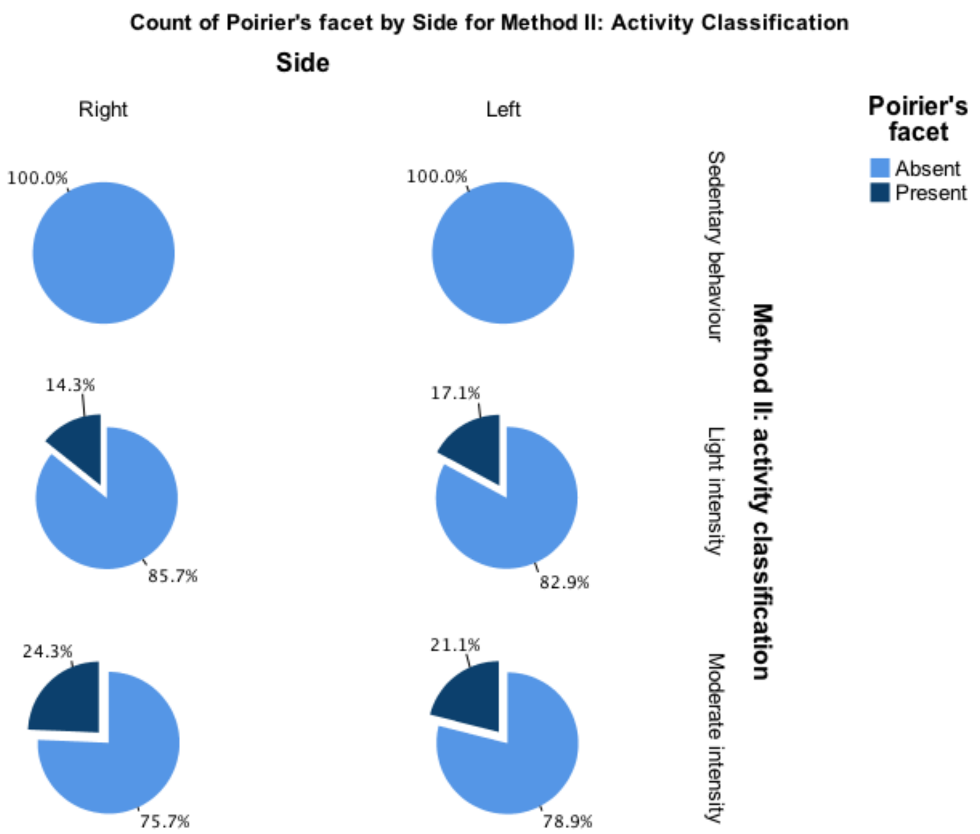


Figure 6-19 Pie charts of Poirier's facets by activity categories, method II, LLC

Table 6-44 Number of femora with & without Poirier's facets by occupational activity categories method II, LLC

Method	Categories	Side	N*	Poirier's facets	
				Absent	Present
Method II	Sedentary behaviour	Left	15	15	0
		Right	15	15	0
		Total	30	30	0
	Light intensity	Left	35	29	6
		Right	35	30	5
		Total	70	59	11
	Moderate Intensity	Left	38	30	8
		Right	37	28	9
		Total	75	58	17

*N = total number of observable femora

For method III (see Figure 6-20 and Table 6-45), there was an increase in percentage of Poirier's facets observed on femora for the left and right sides from non-manual to manual. When not separated by side there is an overall increase from 11.9% for the non-manual group to 16.9% for the manual group.

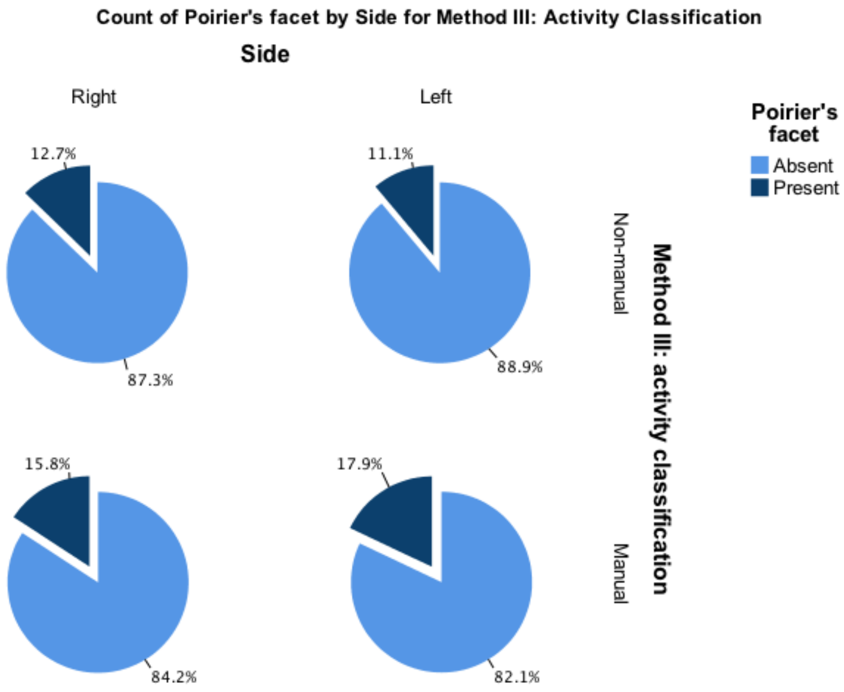


Figure 6-20 Pie charts of Poirier's facets by activity categories, method III, LLC

Table 6-45 Number of femora with & without Poirier's facets by occupational activity method III, LLC

Method	Categories	Side	N*	Poirier's facets	
				Absent	Present
Method III	Non-manual	Left	54	48	6
		Right	55	48	7
		Total	109	96	13
	Manual	Left	39	32	7
		Right	38	32	6
		Total	77	64	13

*N = total number of observable femora

Plaque

Figure 6-21 shows the percentage (of observable femora) for each plaque type per activity category for activity classification method I, while Table 6-46 shows the number of femora with each plaque type for each category. When considering both sides together for the low activity group type A was observed on 10.3%, type B on 22.4% and type C on 8.6% of observable femora. For the moderate activity group, type A was recorded on 2.4%, type B on 38.1% and type C on 11.9% of observable femora. While for the high activity group type A was recorded on 6.7%, type B on 24.0% and type C on 12.0% of observable femora.

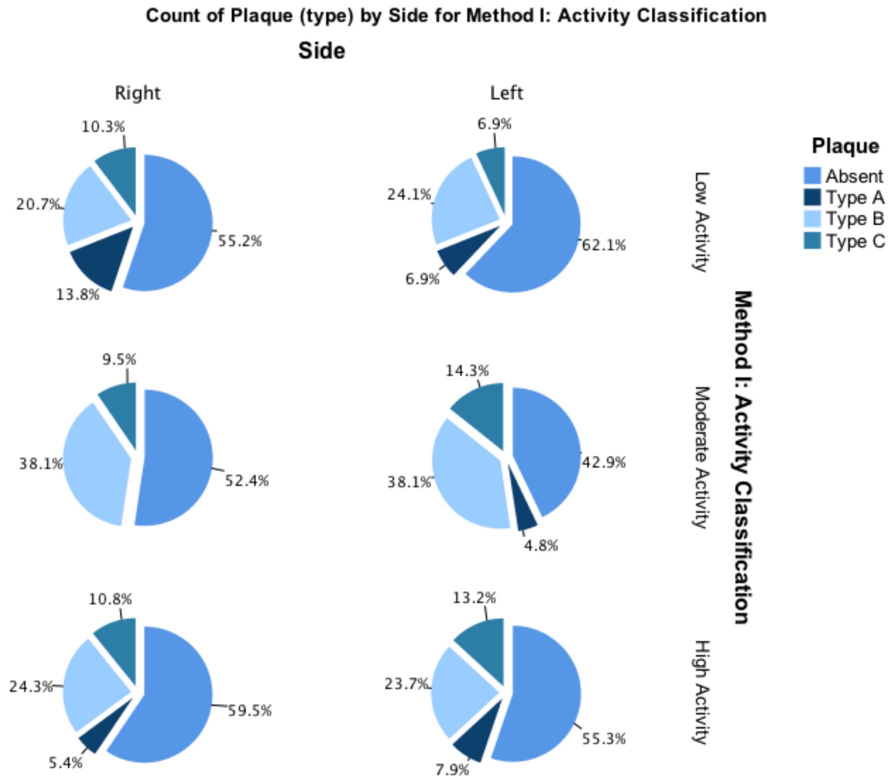


Figure 6-21 Pie charts of plaque by activity categories, method I, LLC

Table 6-46 Number of femora with & without plaque by occupational activity method I, LLC

Method	Categories	Side	N*	Plaque			
				Absent	Type A	Type B	Type C
Method I	Low Activity	Left	29	18	2	7	2
		Right	29	16	4	5	3
		Total	58	34	6	13	5
	Moderate Activity	Left	21	9	1	8	3
		Right	21	11	0	8	2
		Total	42	20	1	16	5
	High Activity	Left	38	21	3	9	5
		Right	37	22	2	9	4
		Total	75	43	5	18	9

*N = total number of observable femora

Figure 6-22 shows the percentage (of observable femora) and Table 6-47 shows the number, of each plaque type per activity category for activity classification method II. When considering both sides together for the sedentary behaviour group type A was observed on 13.3%, type B on 16.7% and type C on 13.3% of observable femora. For the light intensity group type A was recorded on 4.3%, type B on 34.3% and type C on 8.6% of observable femora. While for the moderate intensity group, type A was recorded on 6.7%, type B on 24.0% and type C on 12.0% of observable femora.

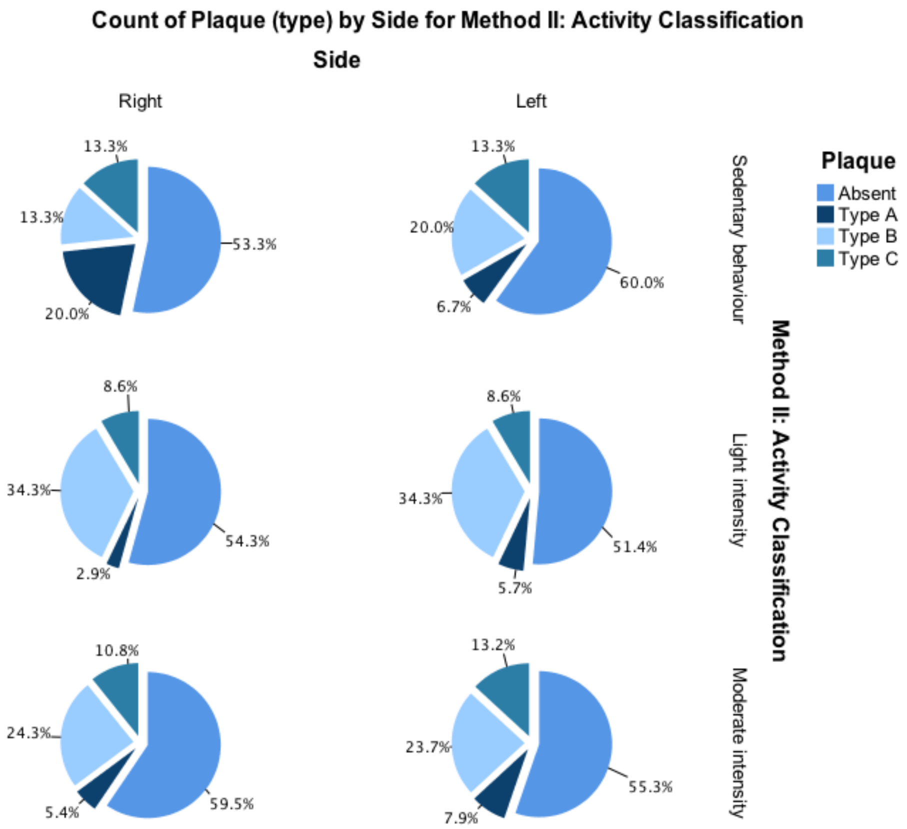


Figure 6-22 Pie charts of plaque by activity categories, method II, LLC

Table 6-47 Number of femora with & without plaque by occupational activity method II, LLC

Method	Categories	Side	N*	Plaque			
				Absent	Type A	Type B	Type C
Method II	Sedentary behaviour	Left	15	9	1	3	2
		Right	15	8	3	2	2
		Total	30	17	4	5	4
	Light intensity	Left	35	18	2	12	3
		Right	35	19	1	12	3
		Total	70	37	3	24	6
	Moderate intensity	Left	38	21	3	9	5
		Right	37	22	2	9	4
		Total	75	43	5	18	9

*N = total number of observable femora

Figure 6-23 shows the percentage (of observable femora) and Table 6-48 shows the number, of each plaque type per activity category for activity classification method III. When considering both sides together for the non-manual group type A was observed on 7.3%, type B on 27.5% and type C on 12.8% of observable femora. For the manual group type A was recorded on 5.2%, type B on 22.1% and type C on 15.6% of observable femora.

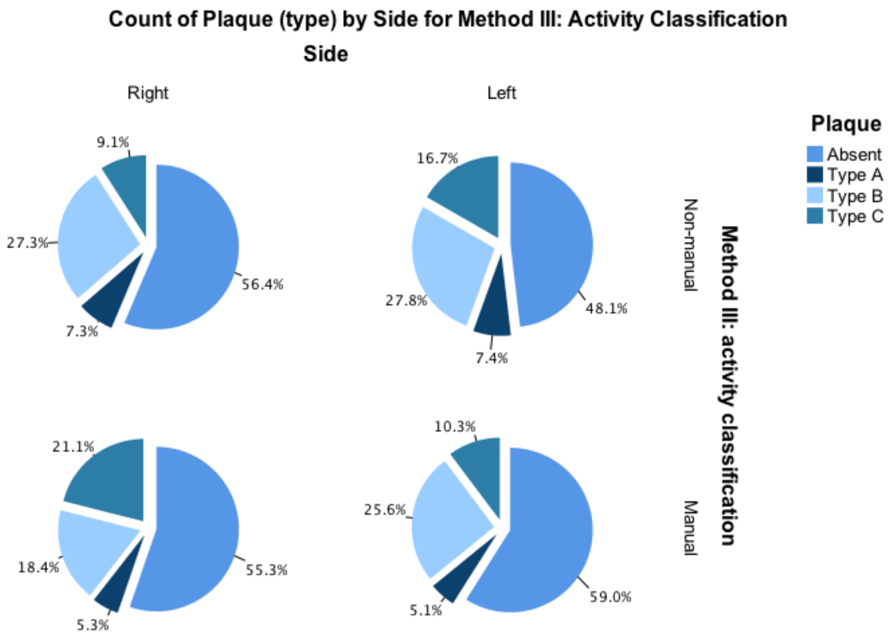


Figure 6-23 Pie charts of plaque by activity categories, method III, LLC

Table 6-48 Number of femora with & without plaque by occupational activity method III, LLC

Method	Categories	Side	N*	Plaque			
				Absent	Type A	Type B	Type C
Method III	Non-manual	Left	54	26	4	15	9
		Right	55	31	4	15	5
		Total	109	57	8	30	14
	Manual	Left	39	23	2	10	4
		Right	38	21	2	7	8
		Total	77	44	4	17	12

*N = total number of observable femora

Cribra

Figure 6-24 shows the percentage (of observable femora) for each cribra type per activity category for activity classification method I, while Table 6-49 shows the number of femora per category. When considering both sides together, for the low activity group type I was observed on 10.3% and type II on 3.4% of observable femora. For the moderate activity group type I was recorded on 31.0% and type II on 0% of observable femora. While for the high activity group type I was recorded on 5.3% and type II on 0% of femora.

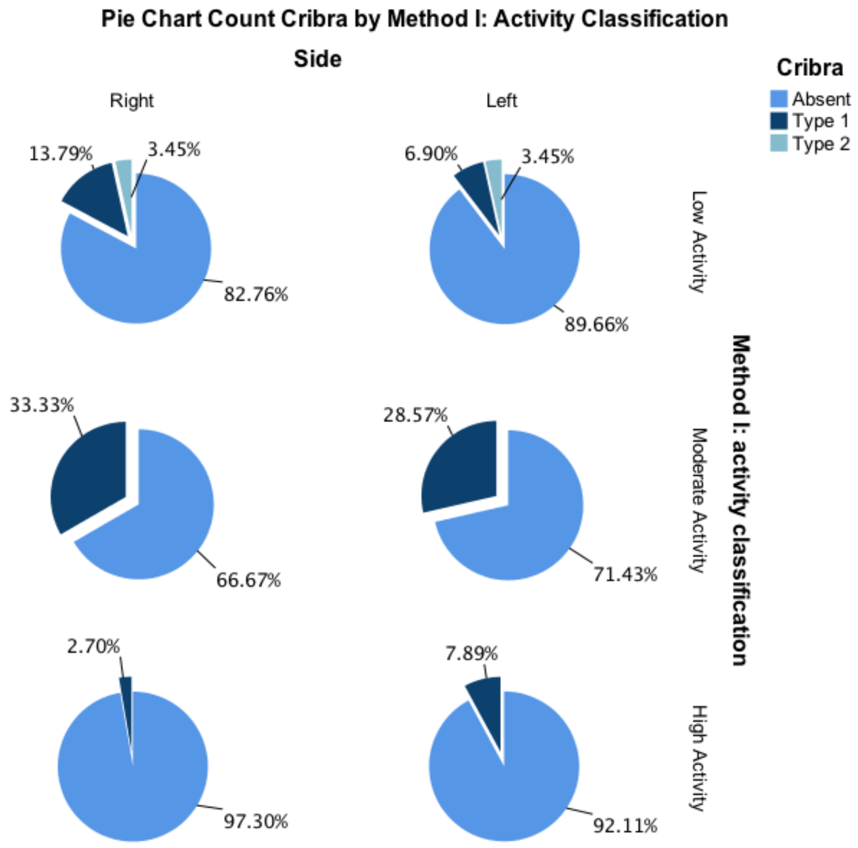


Figure 6-24 Pie charts of cribra by activity categories, method I, LLC

Table 6-49 Number of femora with & without cribra by occupational activity method I, LLC

Method	Categories	Side	N*	Plaque		
				Absent	Type I	Type II
Method I	Low Activity	Left	29	26	2	1
		Right	29	24	4	1
		Total	58	50	6	2
	Moderate Activity	Left	21	15	6	0
		Right	21	14	7	0
		Total	42	29	13	0
	High Activity	Left	38	35	3	0
		Right	37	36	1	0
		Total	75	71	4	0

*N = total number of observable femora

For method II, when considering both sides together, for the sedentary behaviour group type I was observed on 10.0% and type II on 0.0% of observable femora. For the light intensity group type I was recorded on 22.9% and type II on 2.9% of observable femora. While for the moderate intensity group type I was recorded on

5.3% and type II on 0.0%. Figure 6-25 shows the percentage of femora per cribra type for each activity group by side, while Table 6-50 shows the number of femora.

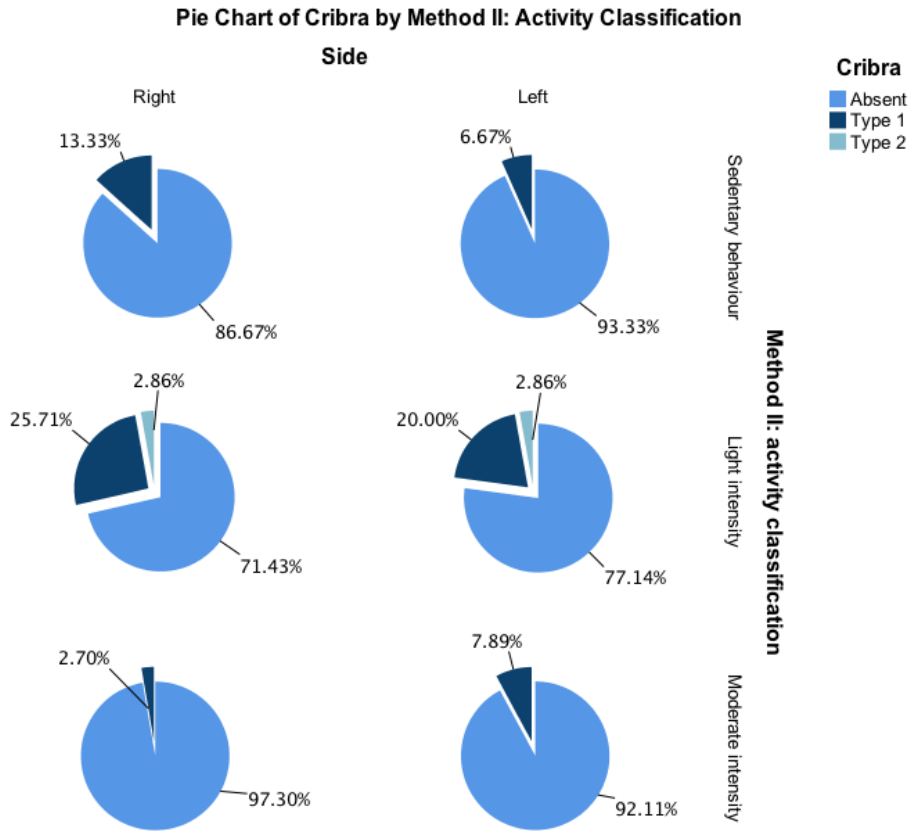


Figure 6-25 Pie charts of cribra by activity categories, method II, LLC

Table 6-50 Number of femora with & without cribra by occupational activity method II, LLC

Method	Categories	Side	N*	Cribra		
				Absent	Type I	Type II
Method II	Sedentary behaviour	Left	15	14	1	3
		Right	15	13	2	0
		Total	30	27	3	0
	Light intensity	Left	35	27	7	1
		Right	35	25	9	1
		Total	70	52	16	2
	Moderate intensity	Left	38	35	3	0
		Right	37	36	1	0
		Total	75	71	4	0

*N = total number of observable femora

Figure 6-26 shows the percentage (of observable femora) for each cribra type per activity category for activity classification method III and Table 6-51 shows the number of femora. When considering both sides together for the non-manual group, type I was observed on 11.0% and type II on 1.8% of observable femora. For the manual group, type I was recorded on 13.0% and type II on 0.0% of observable femora.

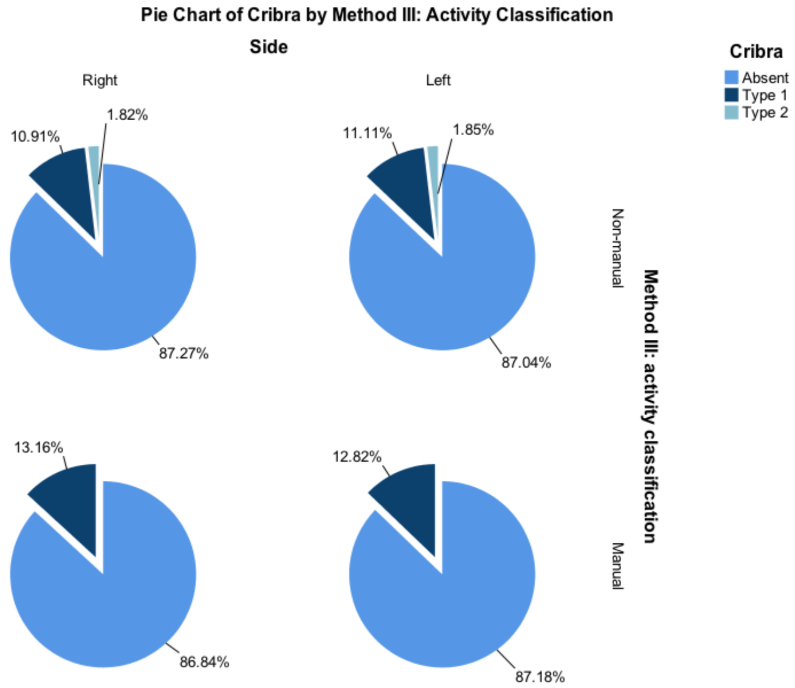


Figure 6-26 Pie charts of cribra by activity categories, method III, LLC

Table 6-51 Number of femora with & without cribra (by type) by occupational activity method III, LLC

Method	Categories	Side	N*	Plaque		
				Absent	Type I	Type II
Method III	Non-manual	Left	54	47	6	1
		Right	55	48	6	1
		Total	109	95	12	2
	Manual	Left	39	34	5	0
		Right	38	33	5	0
		Total	77	67	10	0

*N = total number of observable femora

6.6.3. Alpha angles by occupational group

Spearman's rank test for the right side showed there was not a significant correlation between alpha angles and MET value, r_s= *0.129, p= 0.247.* For the left side, there was also no significant correlation, r_s= *0.065, p= 0.547.*

Further to this, statistical analysis was run to determine if there was a significant difference in mean alpha angle size between occupation and occupational physical activity categories. The descriptive statistics for alpha angle size for the ISCO-08 occupation classification categories are shown in Table 6-52 below. One-way ANOVAs, for both sides did not find a significant difference in alpha angle size between each category.

For the right side, there was no significant difference in mean alpha angle size between the occupational categories, $F(7,94) = 1.010, p = 0.429$. The alpha angle data was not normally distributed for the 'clerical support workers' and 'undetermined' categories. It was not possible to transform the clerical support workers alpha angle data to reach normality therefore a comparison non-parametric test was run. The Kruskal-Wallis test showed no significant difference in median alpha angle size between the categories, $\chi^2(7) = 6.515, p = 0.481$. The highest mean alpha angles were recorded for elementary occupations, as shown in Figure 6-27, followed by services and sales workers, then technicians and associate professionals. The lowest mean alpha angles were recorded for clerical support workers.

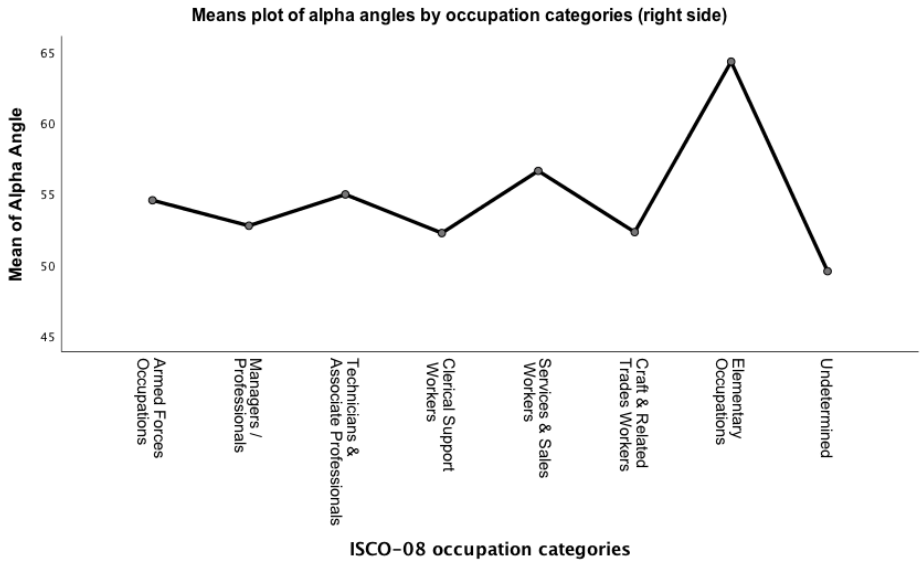


Figure 6-27 Means plot of alpha angles by occupation categories, right side, LLC

For the left side there was no significant difference in mean alpha angle size between the occupation categories, $F(7,97) = 0.971, p = 0.456$. The alpha angle data for the 'crafts and related trades workers' was not normally distributed however n>30. The highest mean alpha angles were recorded for elementary occupations followed by armed forces occupations then managers/professionals, as shown in Figure 6-28. The lowest mean alpha angles are recorded for the undetermined category.

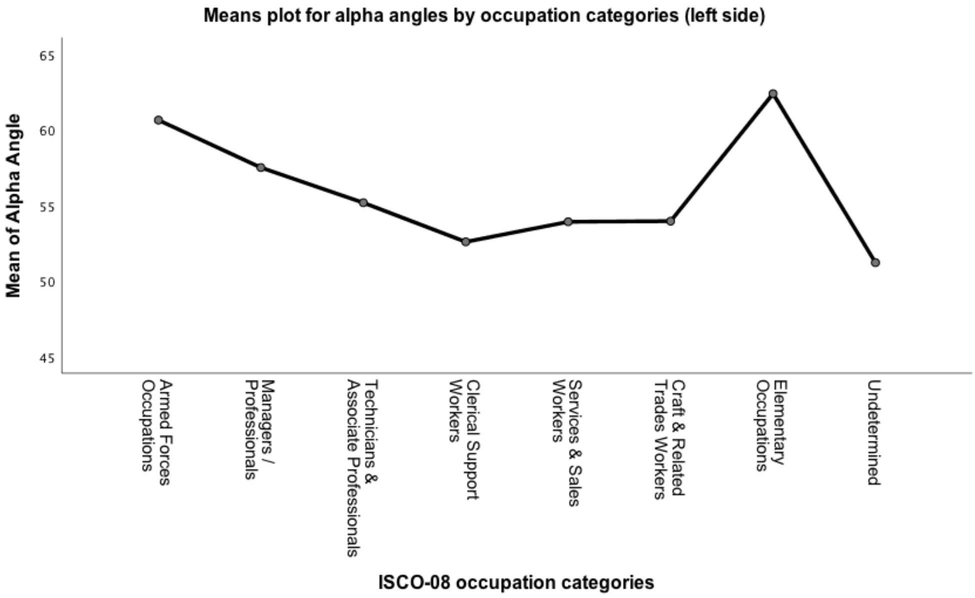


Figure 6-28 Means plot of alpha angles by occupation categories, left side, LLC

The descriptive statistics for alpha angle size by occupational activity categories for method I are shown in Table 6-53 below. A one-way ANOVA test for the right side showed there was no statistically significant difference between alpha angle size and occupational activity group, $F(2,80) = 0.756, p = 0.473, \eta^2=0.019$. The alpha angle size increased from low activity (52.59° ± 11.73°) to moderate activity (53.07° ± 9.74°) to high activity (55.89° ± 12.08°). The alpha angle data for the low activity group was however not normally distributed (p = 0.011) and the data could not be transformed to reach normality therefore a comparison Kruskal-Wallis test was run which also found no significant difference between group medians, $\chi^2(2)= 1.422, p = 0.491$.

For the left side, alpha angle size decreased from low activity (54.49° ± 11.16°) to moderate activity (53.28° ± 9.14°) then increased to high activity (55.57° ± 11.97°). There was no statistically significant difference between alpha angle size and occupational activity group, $F(2,84) = 0.293, p = 0.746, \eta^2=0.007$.

Table 6-52 Descriptive statistics showing alpha angle size by ISCO-08 occupation categories, LLC

side	Categories	N	Mean (°)	Min (°)	Max (°)	Range (°)	Std. Dev
Left femora	Armed Forces Occupations	7	60.65	50.96	73.86	22.90	7.95
	Managers/ Professionals	10	57.50	40.35	76.91	36.56	11.22
	Technicians and Associate Professionals	7	55.18	39.59	69.65	30.06	12.13
	Clerical support workers	11	52.59	33.63	69.72	36.09	10.84
	Services and sales workers	20	53.91	38.59	76.97	38.38	11.61
	Craft and related trades workers	35	53.96	37.56	74.55	36.99	10.33
	Elementary occupations	4	62.39	42.59	75.83	33.24	14.56
	Undetermined	11	51.21	39.09	63.07	23.98	8.50
Right femora	Armed Forces Occupations	8	54.55	38.49	69.36	30.87	10.91
	Managers/ Professionals	10	52.76	35.10	67.33	32.23	10.44
	Technicians and Associate Professionals	7	54.96	39.98	65.65	25.67	9.83
	Clerical support workers	12	52.24	34.15	68.52	34.37	13.89
	Services and sales workers	18	56.62	36.95	80.03	43.08	11.90
	Craft and related trades workers	32	52.31	34.48	75.71	41.23	10.58
	Elementary occupations	4	64.31	52.51	80.12	27.61	12.44
	Undetermined	11	49.55	38.63	69.90	31.27	10.84

Table 6-53 Descriptive statistics showing alpha angle size by method I occupational activity categories, LLC

Method I

	Categories	N	Mean (°)	Min. (°)	Max. (°)	Range (°)	Std. Dev.
Left Femora	Low activity	28	54.49	33.63	76.91	43.28	11.16
	Moderate activity	21	53.28	37.56	69.65	32.09	9.14
	High activity	38	55.57	38.59	76.97	38.38	11.97
Right Femora	Low activity	29	52.59	34.15	68.52	34.37	11.73
	Moderate activity	19	53.07	34.48	73.52	39.03	9.74
	High activity	35	55.89	36.51	80.12	43.61	12.08
Total	Low activity	57	53.52	33.63	76.92	43.28	11.39
	Moderate activity	40	53.18	34.48	73.52	39.03	9.31
	High activity	73	55.72	36.51	80.12	43.61	11.94

The descriptive statistics for alpha angle size by occupational activity categories for method II are shown in Table 6-54 below. A one-way ANOVA for the right side, showed no statistically significant difference between alpha angle size and occupational activity group, $F(2,80) = 0.777,\ p = 0.463,\ \eta^2=0.019.$ The mean alpha angle size increased from sedentary behaviour group (52.16° ± 13.14°) to light intensity group (53.06° ± 9.90°) to moderate intensity group (55.89° ± 12.08°). The alpha angle data for the low activity group was not normally distributed (p = 0.039) and this data could not be transformed. A Kruskal-Wallis test was therefore run which also found no significant difference between groups $\chi^2(2)= 1.468,\ p = 0.480.$

For the left side, alpha angle size increased from sedentary behaviour group (53.22° ± 11.03°) to light intensity group (54.27° ± 10.08°) to moderate intensity group (55.57° ± 11.97°). There was no statistically significant difference between alpha angle size and occupational activity group, $F(2,84) = 0.266,\ p = 0.767,\ \eta^2=0.006.$

Table 6-54 Descriptive statistics showing alpha angle size by method II occupational activity categories, LLC

Method II

	Categories	N	Mean (°)	Min. (°)	Max. (°)	Range (°)	Std. Dev.
Left Femora	Sedentary behaviour	14	53.22	33.63	69.72	36.09	11.03
	Light intensity	35	54.27	37.56	76.91	39.35	10.08
	Moderate intensity	38	55.57	38.59	76.97	38.38	11.97
Right Femora	Sedentary behaviour	15	52.16	34.15	68.52	34.37	13.14
	Light intensity	33	53.06	34.48	73.52	39.03	9.90
	Moderate intensity	35	55.89	36.51	80.12	43.61	12.08
Total	Sedentary behaviour	29	52.67	33.63	69.72	36.09	11.96
	Light intensity	68	53.68	34.48	76.91	42.43	9.94
	Moderate intensity	73	55.72	36.51	80.12	43.61	11.94

The descriptive statistics for alpha angle size by occupational activity categories for method III are shown in Table 6-55 below. Due to only two categories being present in this activity method independent sample t-tests were conducted. For the right side, alpha angle size was extremely similar for the non-manual (53.85° ± 11.49°) and manual group (53.39° ± 11.32°). There was no statistically significant difference found between alpha angle size and occupational activity group, $t(88) = 0.185,\ p = 0.853.$

For the left side, alpha angle size was also extremely similar for the non-manual (53.91° ± 10.72°) and manual group (53.67° ± 10.76°). There was no statistically significant difference found between alpha angle size and occupational activity group, *$t(91) = 0.109$, $p = 0.913$.*

Table 6-55 Descriptive statistics showing alpha angle size by method III occupational activity categories, LLC

Method III

	Categories	N	Mean (°)	Min. (°)	Max. (°)	Range (°)	Std. Dev.
Left Femora: α angles	Non-manual	54	53.92	33.63	76.97	43.34	10.72
	Manual	39	53.67	37.56	75.83	38.27	10.76
Right Femora: α angles	Non-manual	53	53.85	34.15	80.03	45.88	11.49
	Manual	37	53.39	34.48	80.12	45.64	11.32
Total	Non-manual	107	53.88	33.63	80.03	46.40	11.06
	Manual	76	53.54	34.48	80.12	45.64	10.96

Alpha angles by occupational group side asymmetry

In order to determine if there was a significant difference in alpha angle size between the left and right femora for each of the occupations from ISCO-08 occupation classification system paired sample t-tests were run (see Table 6-56). Only individuals with both femora were included.

For the ISCO-08 occupation classification system, there was only a significant difference in mean alpha angle size between left and right sides for the armed forces occupations. The mean alpha angle size was significantly higher for the left side (60.65°± 7.95°) than the right (53.48°± 11.32°) side, *$t(6)= 2.58$, $p= 0.042$.*

For the managers/professionals the mean alpha angle size was higher for the left side (57.50° ± 11.22°) than the right side (52.76° ± 10.44°) however this difference was not significant, *$t(9)= 1.186$, $p= 0.266$.* The difference data between the left and right side was not normally distributed *($p=0.005$)* therefore a non-parametric comparison Wilcoxon signed rank test was run which also found no significant difference in median alpha angle size between sides, *$z = 0.296$, $p= 0.767$.* Technicians and associated professionals showed a higher alpha angle for the left side (55.18° ± 12.13) compared to the right side (54.96° ± 9.83) however this was not significantly different, *$t(6)= 0.060$,* *p= 0.954.* For clerical support workers, mean alpha angle size was higher for the right side (53.89° ± 13.29) when compared to the left (52.59° ± 10.84) however this difference was not found to be significant, *t(10)= -0.522, p= 0.613.* There was also no significant difference between mean alpha angle size between left (53.43°± 11.68) and right side (56.62°± 11.90) for the service and sales workers category, *t(17)=-1.309, p= 0.208.* Mean alpha angle size was not significantly different between left (53.75°± 10.74) and right (52.31°± 10.58) side for craft and related trades workers, *t(31)= 0.996, p= 0.327.* Elementary occupations also showed no significant difference between alpha angle size for the left (62.39°± 14.56) and right sides (64.31°± 12.44), *t(3)= -0.401, p= 0.715.*

Table 6-56 Paired sample t-test results for ISCO-08 occupation categories alpha angle by side, LLC

		Paired differences			95% confidence interval				
Alpha angles	categories	Mean	Std. dev	Std. error mean	Lower	Upper	t	df	Sig. (2-tailed)
Left side–right side	Armed forces occupations	7.17	7.36	2.78	0.37	13.97	2.58	6	0.042
	Managers/ Professionals	4.75	12.65	4.11	-4.31	13.80	1.19	9	0.266
	Technicians and Associate Professionals	0.22	9.48	3.58	-8.56	8.99	0.06	6	0.954
	Clerical support workers	-1.30	8.27	2.49	-6.86	4.25	-0.52	10	0.613
	Services and sales workers	-3.18	10.32	2.43	-8.32	1.95	-1.31	17	0.21
	Craft and related trades workers	1.45	8.21	1.45	-1.51	4.41	1.00	31	0.33
	Elementary occupations	-1.91	9.55	4.77	-17.10	13.28	-0.40	3	0.72
	Undetermined	1.81	9.93	3.14	-5.29	8.91	0.58	9	0.58

Alpha angles and non-metric traits by occupational physical activity group

To establish if occupational physical activity had an impact on the difference in alpha angle size between femora with and without non-metric traits, one-way ANCOVAs were run on the left and right side separately, controlling for MET values. In addition to this, two-way ANOVAs were run to determine if there was a statistically significant interaction effect between the different methods for categorising occupational activity and the presence of non-metric traits on alpha angle size.

Poirier's facets

For the right side, after adjusting for MET values, there was still a significant difference in mean alpha angle size between femora with Poirier's facets present compared to those absent for Poirier's facets, $F(1,80) = 37.820$, $p = <0.0005$. The left side also still showed a statistically significant difference in mean alpha angle size when adjusting for MET values, $F(1,83)= 0.347$, $p= 0.558$. The standardised residual data for the absent group was not normally distributed (p = 0.004) therefore a comparison test was run with the alpha angle data transformed however it was not possible to correct for the violation of normality.

For the right side there was not a statistically significant interaction between Poirier's facets and occupational activity category (method I), $F(2,77)= 0.137$, $p= 0.872$. Main effect analysis showed mean alpha angle was not significantly different between the occupational activity categories, $F(2,77)= 0.174$, $p= 0.841$. While there was a significant difference in alpha angle size between femora with and those without Poirier's facets present, $F(1,77)= 29.444$, $p= <0.0005$. The alpha angle data for the group with Poirier's facets absent and in the low activity category was not normally distributed ($p= 0.049$). A comparison test was run with the alpha angle size transformed, which corrected for this violation from normality however this caused a violation to the assumption of homogeneity of variances. This comparison test also showed no significant interaction, $F(2,77)= 0.091$, $p= 0.913$. For the left side, again there was no significant interaction effect between the presence of Poirier's facets and occupational activity group (method I) on alpha angle size, $F(2,81)= 0.209$, $p= 0.812$. Main effect analysis showed alpha angle size was not significantly different between occupational activity groups, $F(2,81)= 0.563$, $p= 0.572$, however there was between femora with and without Poirier's facets, $F(1,81) = 8.975$, $p= 0.004$. The alpha angle data for femora absent for Poirier's facets and categorised as high activity was not normally distributed ($p = 0.123$) however a transformation of the alpha angle data could not correct for this violation of normality.

For occupational physical activity method II on the right side there was not a statistically significant interaction between Poirier's facets and occupational physical activity category (method II) on alpha angle size, *F(1,78)=0.015, p= 0.903.* There was however a significant difference in alpha angle size between femora with and without Poirier's facets, *F(1, 78)= 36.451, p= <0.0005.* While mean alpha angle size was not significantly different between occupational activity categories, *F(2, 78)= 0.163, p=0.850.* The assumption of the homogeneity of variances was not met (*p= 0.002*) and therefore a comparison test was run to determine if this violation would affect conclusions. It was not however possible to transform the data to meet this assumption. For the left side, again there was not a significant interaction between the presence of Poirier's facets and occupational activity categories on alpha angle size, *F(1,82)= 0.122, p= 0.728.* The residual data for moderate intensity, Poirier's facets absent was not however normally distributed (*p= 0.006)* and it was not possible to transform the data to reach normality but n=30.

There was also no statistically significant interaction between method III for categorising occupational activity and Poirier's facets on alpha angle size for the right, *F(1,85)=0.327, p=0.569,* or the left side, *F(1,88)=1.702, p= 0.195.* Main effect analysis for both sides also showed a significant difference in mean alpha angle size between femora with and those with Poirier's facet present, for the right side, *F(1,85)= 34.844, p= <0.0005,* and for the left side, *F(1,88)= 11.600, p= 0.001.* There was however no significant difference in mean alpha angle size between occupational activity groups for the right side, *F(1,85)=0.020, p= 0.889,* and the left side, *F(1,88)=1.490, p= 0.225.* The residual alpha angle data for femora absent for Poirier's facets and categories as manual for occupational activity was not normally distributed (*p= 0.016*). It was no possible to transform the alpha angle data to meet normality however n=32.

Plaque

For the right side after adjusting for MET values there was still a significant difference in mean alpha angle size between femora with different plaque types present and those with plaque absent, *F(3,78)= 3.815, p= 0.013.* Post hoc pairwise analysis was performed with a Bonferroni adjustment and showed a significant difference between type B and type C plaque (*p= 0.011)*. The standardized residual data for alpha angle size was not normally distributed for type c plaque (*p= 0.019)* and there was an outlier present. A comparison test excluding this outlier met the assumption of normality and the test conclusions were no different to the original data test. The post hoc test however showed significant differences in alpha angle size between femora absent for plaque and those with type C plaque present (*p= 0.012),* those with type A present and type C present (*p=0.018),* and femora with type B present and those with type C present *(p= 0.002).*

For the left side, there was also a significant difference in mean alpha angle size between femora with different plaque types and those absent for plaque when adjusted for MET values, $F(3,82)= 6.985$, $p= <0.0005$. Post hoc pairwise analysis with a Bonferroni's correction applied showed a significant difference between type A and absent *(p= 0.003),* type A and type B *(p= 0.004),* type A and type C *(p= <0.0005).* The standardized residual data for alpha angle size was not normally distributed for type C plaque (*p= 0.020)* and there was two outliers present. When these outliers were excluded the assumption of normality was met however the assumption of the homogeneity of variances was violated (*p= 0.003).* The comparison test showed the same conclusions as the original test.

For the right side there was not a statistically significant interaction between plaque type and occupational activity category (method I), $F(5,72)= 1.990$, $p= 0.090$. Main effect analysis showed there was no significant difference in alpha angle size between activity categories (method I), $F(2,72)= 0.372$, $p= 0.691$. There was also no significant difference in alpha angle size between plaque types (and those absent for plaque), $F(3,72)= 2.457$, $p= 0.070$. The residual alpha angle data was not normally distributed for low activity, plaque type A *(p= 0.003*). It was not possible to transform the alpha angle data to meet the assumption of normality. For the left side there was also not a statistically significant interaction between plaque type and occupational activity category (method I) on alpha angle size, $F(6,75)= 0.391$, $p= 0.883$. Main effect analysis showed there was no significant difference in alpha angle size between activity categories (method I), $F(2,75)= 0.193$, $p= 0.825$. There was however a significant difference in alpha angle size between plaque types, $F(3, 75)= 5.045$, $p= 0.003$. Pairwise comparison was therefore run with a Bonferroni's adjustment. This showed femora with type A plaque had significantly higher mean alpha angle than femora absent for plaque (*p= 0.023),* type B *(p= 0.030)* and type C (*p= 0.001).*

When using method II to categorise occupational physical activity the right side showed a statistically significant interaction between these categories and plaque type on mean alpha angle size, *F(6,71)= 2.589, p= 0.025.* Therefore, simple main effect analysis was run with a Bonferroni's adjustment which showed a statistically significant difference in mean alpha angle size for those with occupational activity classification of sedentary behaviour with either plaque absent, type A type B or type C present, *p= 0.006*. There was also a statistically significant difference in mean alpha angle with occupational activity classification of moderate intensity, *p= 0.004.* Pairwise comparison showed, for those with occupations classified as sedentary behaviour, mean alpha angle size was significantly higher for femora with type A present than those with plaque absent, *p= 0.022.* While for those with occupations classified as moderate intensity mean alpha angle size was significantly higher for femora without plaque present than those with type C (*p= 0.007*), type B and type C (*p= 0.005*). Simple main effect analysis only showed a statistically significant difference in mean alpha angle size for femora with plaque absent with either sedentary behaviour, light intensity or moderate intensity occupational activity classification. Pairwise comparison showed for femora with plaque absent, there was statistically significant higher mean alpha angle for moderate intensity compared to sedentary behaviour activity classification, *p= 0.025.* It must be noted however the small numbers per category when considering these results.

For the left side there was not a statistically significant interaction between occupational activity category and plaque on alpha angle size, *F(6,75)= 0.288, p=0.941.* There was however a significant difference in mean alpha angle size between plaque types, *F(3,75)= 5.596, p= 0.002,* but not for occupational activity categories, *F(2,75)= 0.052, p= 0.950.* Main effect analysis with Bonferroni's adjustment applied showed a significantly higher mean alpha angle for type A compared to femora absent for plaque (*p= 0.011),* type B *(p= 0.028)* and type C *(p= 0.001).*

For both sides, with method III of categorising physical activity there was not a statistically significant interaction with plaque on alpha angle size, for the right side *F(3,81)= 1.031, p= 0.384* and for the left side *F(3,84)= 1.078, p= 0.363.* For the right side there was not a statistically significant difference in mean alpha angle size between plaque types, *F(3, 81)= 2.300, p= 0.083* or between physical activity groups, *F(1,81)= 0.129, p= 0.720.* The residuals for alpha angles was not however normally distributed for femora with type A plaque present and categorised as non-manual *(p= 0.003)*. This data could not be transformed to meet the assumption of normality. For the left side there was a statistically significant difference in mean alpha angle size between plaque types, *F(3, 84)= 5.709, p= 0.001.* Pairwise comparison with a Bonferroni's adjustment applied showed the mean alpha angle size was significantly higher for femora with type A plaque present compared to femora absent for plaque (*p= 0.003),* type B *(p= 0.003),* and type C *(p= 0.001).* There was no significant difference in mean alpha angle size between occupational activity groups, *F(1, 84)= 0.121, p= 0.729.*

Chapter 7. Results III: FAI and Non-FAI groups

This chapter focuses on the results from the 3D volume rendered CT models. The sample includes a total of thirty individuals (sixty femora). Eighteen of these individuals were undergoing investigation for FAI (FAI-group) and twelve of these individuals had CT scans taken for reasons other than FAI e.g. trauma (non-FAI group). Males and females were present for both samples. Cribra is not included in the analysis in this section as, due to image quality, it was not possible to observe this trait accurately on the 3D volume rendered images.

Sections 7.1. and 7.2. provide an overview of the alpha angle data and non-metric traits for this sample and to establish if any additional factors are acting on these measurements, such as:

- Side
- Age (continuous scale)

Section 7.3. focuses on determining if there is a significant difference in alpha angle size dependent on the presence/absence of the non-metric traits; Poirier's facets and plaque.

The results in section 7.4. show the difference in proportions of femora with and without cam morphology (using three commonly used alpha angle thresholds from the literature ≥50°, ≥55°, ≥60°) by the presence of non-metric traits.

7.1. Alpha angle information

Distribution of alpha angle size by side

The average alpha angle for the FAI sample (n = 36) was 53.57°. The mean alpha angle for the left femora (n =18) was 54.56° and 52.58° for the right (n = 18). Table 7-5 shows the descriptive statistics for alpha angle size for both sides together, left side only and right side only. Figure 7-1 shows the distribution of alpha angles for each side separately.

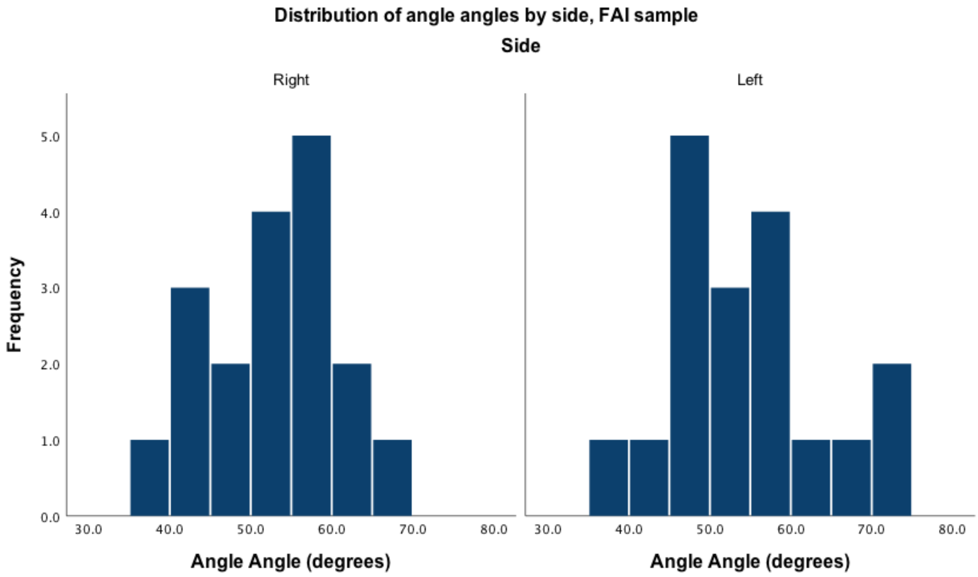


Figure 7-1 Histogram of distribution of alpha angles by side for the FAI group (pooled sex)

Bilateral asymmetry of mean alpha angle size for the FAI group was determined using a paired sample t-test (see Table 7-1 and Table 7-2). The left femora had a higher mean alpha angle than the right femora. The left femora had a mean alpha angle size 1.97°± 11.19° higher than the right femora; this difference was not however statistically significant, *t(17) = 0.749, p = 0.464.*

Table 7-1 Paired samples descriptive statistics for left and right femora alpha angles, FAI group (pooled sex)

Side	N	Mean (°)	Std. Dev	Std. Error Mean
Left	18	54.56	9.93	2.34
Right	18	52.58	7.55	1.78

Table 7-2 Paired sample t-test data table alpha angle size by side, FAI group (pooled for sex)

	Paired differences							
				95% confidence interval				
Alpha angles	Mean	Std. dev	Std. error mean	Lower	Upper	t	df	Sig. (2-tailed)
Left side– right side	1.974	11.187	2.637	-3.590	7.537	0.749	17	0.464

The average alpha angle size for the non-FAI group (n = 24) was 51.06°. The mean alpha angle size for the left femora (n = 12) was 52.46° and 49.66° for the right (n = 12). The distribution of alpha angles for the non-FAI group, by side, are shown in Figure 7-2.

Bilateral asymmetry of mean alpha angle size was determined using a paired sample t-test (see Table 7-3 for descriptive statistics and Table 7-4 for statistical test results). The left femora (52.46° ± 8.56°) had a higher mean alpha angle than the right femora (49.66° ± 7.42°). The left femora had a mean alpha angle size 2.80°± 6.28 higher than the right femora; this difference was not however statistically significant, $t(11) = 1.545$, $p = 0.151$.

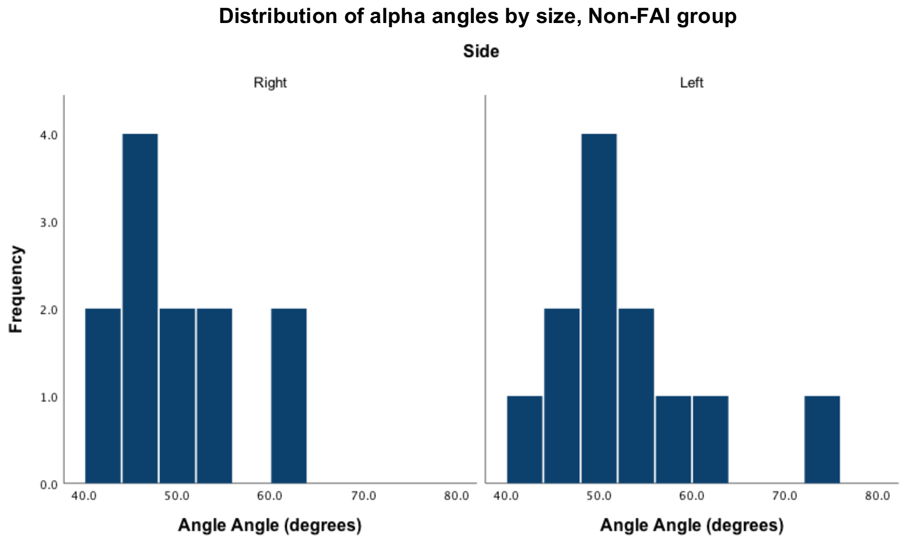


Figure 7-2 Histogram of distribution of alpha angles by side for the non-FAI group (pooled sex)

Table 7-3 Paired samples descriptive statistics for left and right femora alpha angles, non-FAI group, pooled sex

Side	N	Mean (°)	Std. Dev	Std. Error Mean
Left	12	52.46	8.56	2.47
Right	12	49.66	7.42	2.14

Table 7-4 Paired sample t-test data table alpha angle size by side, non-FAI (pooled for sex)

	Paired differences							
				95% confidence interval				
Alpha angles	Mean	Std. dev	Std. error mean	Lower	Upper	t	df	Sig. (2-tailed)
Left side– right side	2.801	6.281	1.813	-1.189	6.792	1.545	11	0.151

There was no significant difference in mean alpha angle size between the FAI and non-FAI groups, as assessed by an independent sample t-test (Table 7-6), for the right side *t(28)=1.047, p=0.304.* For the left side there was also no significant difference in mean alpha angle size between the two groups, *t(28)=0.598, p= 0.555.* The descriptive statistics for alpha angle size for both the FAI and non-FAI groups are shown in Table 7-5.

Table 7-5 Descriptive statistics for alpha angle size by FAI and non-FAI group and side

Group	Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
FAI group	Total	36	39.17	35.55	74.72	53.57	8.75
	Left	18	39.17	35.55	74.72	54.56	9.93
	Right	18	27.18	39.46	66.64	52.58	7.55
Non-FAI group	Total	24	32.92	40.92	73.84	51.06	7.96
	Left	12	31.28	42.57	73.84	52.46	8.56
	Right	12	22.87	40.92	63.79	49.66	7.42

Table 7-6 Independent sample t-test data table for alpha angle between the FAI and non-FAI group for left and right side separately (pooled sex)

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	0.598	28	0.555	2.097	3.508	-5.089	9.284
Right side	1.047	28	0.304	2.925	2.794	-2.799	8.648

Distribution of alpha angle by sex

The descriptive statistics for alpha angle size by sex and side are shown in the Table 7-7. To determine if there was a statistically significant difference in mean alpha angle size between males and females for both the FAI and non-FAI group independent sample t-tests were run (see Table 7-8 the for results of the statistical analysis for the FAI group and Table 7-9 for the non-FAI group). For the FAI group, on the right side, alpha angle size for males was statistically significantly higher than for females, $p = 0.009$. While for the left side there was no significant difference, however the mean alpha angle size was higher for females compared to males, $p = 0.442$.

For the non-FAI, on the right side, the alpha angle data for males was not normally distributed and it was not possible to transform the data to reach normality ($p = 0.026$) therefore a Mann-Whitney U non-parametric test was run. This showed no significant difference in alpha angle size between males and females although it was higher for males than females, p= 0.530. For the left side alpha angle data was normally distributed for both males and females. There was again no significant difference between males and females, $p = 0.284$.

Table 7-7 Descriptive statistics for alpha angle size by sex for FAI and non-FAI group

	Sex	Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
FAI	Males	Right	12	22.24	44.40	66.64	55.67	6.30
		Left	12	39.17	35.55	74.72	53.24	10.57
		All	24	39.17	35.55	74.72	54.45	8.60
	Females	Right	6	17.30	39.46	56.77	46.42	6.17
		Left	6	23.08	47.85	70.93	57.19	8.76
		All	12	31.47	39.46	70.93	51.81	9.16
Non-FAI	Males	Right	7	19.35	44.43	63.79	51.65	8.37
		Left	7	31.28	42.57	73.84	54.79	10.30
		All	14	31.28	42.57	73.84	53.22	9.16
	Females	Right	5	11.48	40.92	52.40	46.87	5.45
		Left	5	11.24	44.95	56.20	49.19	4.41
		All	10	15.28	40.92	56.20	48.03	4.83

Table 7-8 Independent sample t-test showing alpha angle size for each side, FAI group

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	-0.788	16	0.442	-3.957	5.021	-14.600	6.686
Right side	2.957	16	0.009	9.249	3.128	2.618	15.879

Table 7-9 Independent sample t-test showing alpha angle size for each side, non-FAI group

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	1.133	10	0.284	5.606	4.947	-5.417	16.629

Distribution of alpha angle size by age

The FAI and non-FAI groups were combined in for analysis of alpha angle size by age to increase the sample size under analysis. A Pearson's correlation for the left side showed a weak negative correlation between alpha angle size and age, however this was not significant, *r(30) = 0.158, p = 0.404*. The right side also showed a weak but positive correlation that was also not significant *r(30) = -0.191, p = 0.313.* The scatterplots in Figure 7-3, for the right and left side separately, shows there is not clear pattern between the two variables.

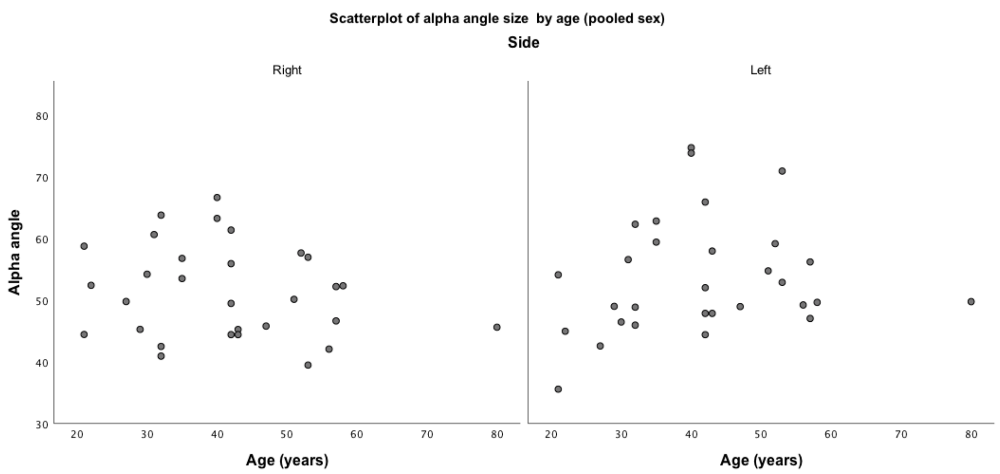


Figure 7-3 Scatterplot of alpha angle size by age, FAI and non-FAI group combined and sex

Table 7-10 Number of femora per age range category by sex, FAI and non-FAI group combined

Age Ranges	Number of males	Number of females	Number of individuals	Number of femora	Percentage of femora
18-29 years	4	1	5	10	16.7%
30-49 years	11	5	16	32	53.3%
50+ years	4	5	9	18	30.0%
Total	19	11	30	60	100.0%

The number of individuals per age range category is shown in Table 7-10 and the descriptive statistics for alpha angle size per age range category is shown in table 7-11 below. For the left side mean alpha angle size increased from 18-29 years group (45.23° ± 6.969) to the 50+ years group (54.39° ± 7.31°) to the 30-49 years group (55.99° ± 9.82°). The mean alpha angle size was not however statistically significantly different between the age groups, $F(2,27)=2.919$, $p= 0.071$, $\eta^2= 0.178$ as shown by a one-way ANOVA. For the right side, there was an increase in mean alpha angle size from 50+ years (49.22° ± 6.29°) to 18-29 years group (50.12° ± 5.83°) to 30-49 years group (53.05° ± 8.52°). This difference was not however found to be significant, $F(2,27)=0.826$, $p=0.448$, $\eta^2=0.058$.

Table 7-11 Descriptive statistics for alpha angle size by age range category, FAI and non-FAI group combined and sex

Age range	Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
18-29 years	Right	5	14.32	44.43	58.75	50.12	5.83
	Left	5	18.55	35.55	54.10	45.23	6.96
	All	10	23.30	35.55	58.75	47.68	6.58
30-49 years	Right	16	25.72	40.92	66.64	53.05	8.52
	Left	16	30.33	44.40	74.72	55.99	9.82
	All	32	33.80	40.92	74.72	54.52	9.16
50+ years	Right	9	18.18	39.46	57.65	49.22	6.29
	Left	9	23.91	47.02	70.93	54.39	7.31
	All	18	31.47	39.46	70.93	51.81	7.13

7.2. Prevalence of non-metric traits

Poirier's facets

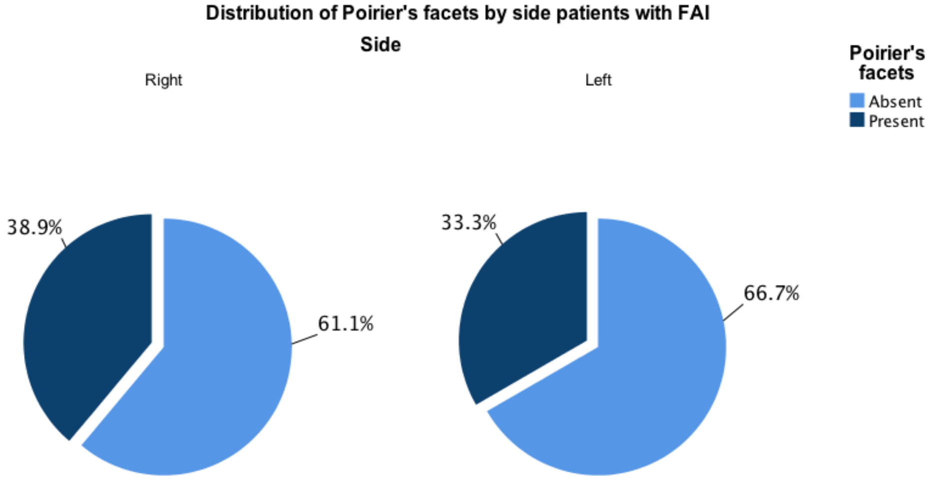


Figure 7-4 Pie charts of Poirier's facets for FAI group, pooled sex,

For the FAI group, of the 36 femora analysed, Poirier's facets were present on 13 (36.1%), absent on 23 (63.9%). For the left side, Poirier's facets were present on 6 femora (33.3%) and absent on 12 femora (66.7%) (see Figure 7-4). While for the right Poirier's facets were present on 7 femora (38.9%) and absent on 11 femora (61.1%) (see Figure 7-4).

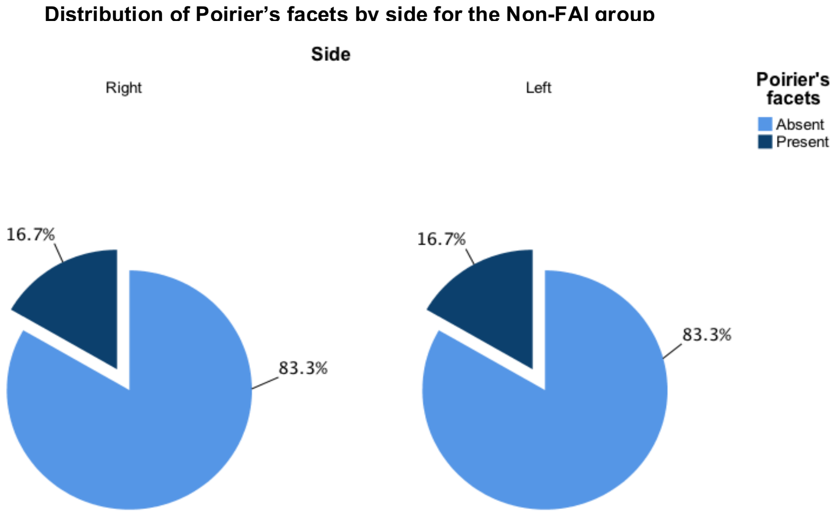


Figure 7-5 Pie charts of Poirier's facets for the non-FAI group, pooled sex

For the non-FAI sample of the 24 femora analysed Poirier's facets were present on 4 (16.7%) and absent on 20 (83.3%). For both the right and left sides Poirier's facets were present on 2 femora (16.7%) and absent on 10 (83.3%) (see Figure 7-5).

A total of 18 individuals in the FAI group (36 femora) had both femora present and analysed for the presence of Poirier's facets (Table 7-12). Of these, 10 (55.6%) individuals were absent for Poirier's facets on both femora, 5 (27.8%) individuals had bilateral Poirier's facets present, 3 (16.7%) individuals had unilateral Poirier's facets present.

Table 7-12 cross tabulation of the occurrence of Poirier's facets by left and right side, FAI group

Poirier's facets		Right Side		
		Present	Absent	Total
Left Side	Present	5	1	6
	Absent	2	10	12
	Total	7	11	18

A total of 12 individuals in the non-FAI group (24 femora) had both femora present and analysed for the presence of Poirier's facets (Table 7-13). Of these, 10 (83.3%) individuals were absent for Poirier's facets bilaterally, 2 (16.7%) individuals had bilateral Poirier's facets present, 0 individuals had unilateral Poirier's facets present.

Table 7-13 cross tabulation of the occurrence of Poirier's facets by left and right side, non-FAI

Poirier's facets		Right Side		
		Present	Absent	Total
Left Side	Present	2	0	2
	Absent	0	10	10
	Total	2	10	12

When the two groups were combined, 34.2% of male femora and 18.2% of female femora had Poirier's facet present. Of the Poirier's facets present in the sample 76.5% were recorded on male and 23.5% on female femora. Table 7-14 shows the number of femora with and without Poirier's facet present for males and females.

Table 7-14 Count of femora categorised for the presence or absence of Poirier's facets by sex and side, FAI and non-FAI groups combined.

Sex	Side	Absent	Present	Total
Male	Left	13	6	19
	Right	12	7	19
	Total	**25**	**13**	**38**
Female	Left	9	2	11
	Right	9	2	11
	Total	**18**	**4**	**22**
Total		**43**	**17**	**60**

Again, the FAI and non-FAI were combined to increase numbers under analysis. With regards to age range categories, there was an increase in the percentage of Poirier's facets recorded with an increase in age range category. Poirier's facets were present on 0.0% of observable femora in the 18-29 years group, 34.4% of the 30-49 years group and 33.3% within the 50+ years age group (see Tables 7-15 and 7-16).

Table 7-15 Count of femora categorised for presence or absence of Poirier's facets by age range category for FAI and non-FAI combined.

Age group	Absent	Present	Total
18-29 years	10	0	10
30-49 years	21	11	32
50+ years	12	6	18
Total	**43**	**17**	**60**

Table 7-16 Percentage of Poirier's facets for observable femora within and between age groups, with FAI and non-FAI combined

Age group	% of femora absent for Poirier's facets within age group	% of femora present for Poirier's facets within age group	% of femora absent for Poirier's facets within the sample	% of femora present for Poirier's facets within the sample
18-29 years	100.0%	0.0%	23.3%	0.0%
30-49 years	65.6%	34.4%	48.8%	64.7%
50+ years	66.7%	33.3%	27.9%	35.3%

Due to the presence of exact age data it was possible to run an independent sample t-test to determine if there was a significant difference in mean age between individuals with Poirier's facets absent or present (Figure 7-6 shows the spread of data for femora with Poirier's facets absent and present by side). For the right side there was no significant difference *t(28)= -1.223, p= 0.136.* There was also no significant different for the left side, *t(28)= -0.676, p = 0.505.*

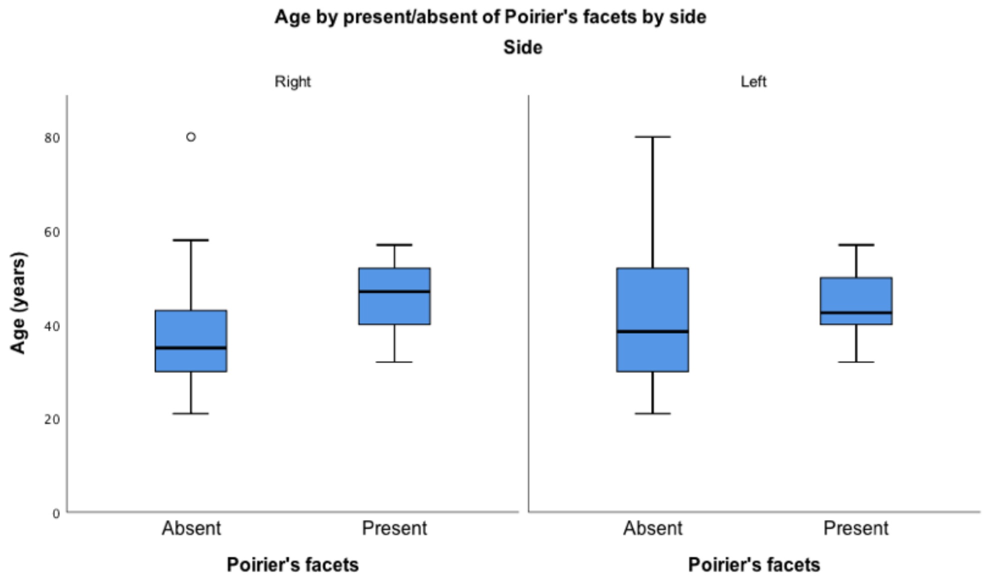


Figure 7-6 Pie charts of age by absence/presence of Poirier's facets, pooled sex and sample, FAI and non-FAI combined

When comparing the prevalence rates of Poirier's facets between the FAI and non-FAI groups a fisher's exact test showed no significant difference in the proportion of Poirier's facets present or absent between the two groups (*p= 0.219)* on the right side or the left side (p= 0.419)

Plaque

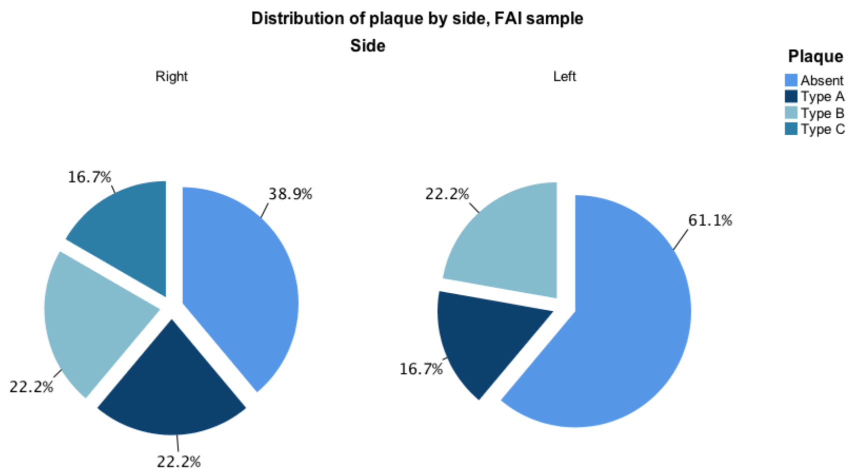


Figure 7-7 Pie charts of the distribution of plaque for FAI group

For the FAI group, plaque was present on 18 (50.0%) and absent on 18 (50.0%) of femora. Seven femora had type A (19.4%), 8 (22.2%) had type B and 3 (8.3%) had type C. For the left side, type A was present on 3 femora, type B was present on 4 femora, type C was present on 0 femora, while plaque was absent on 11 left femora. For the right side, type A plaque was present on 4 femora, type B was present on 4 femora; type C was present on 3 femora, while femora 7 right femora were absent for plaque (see Figure 7-7).

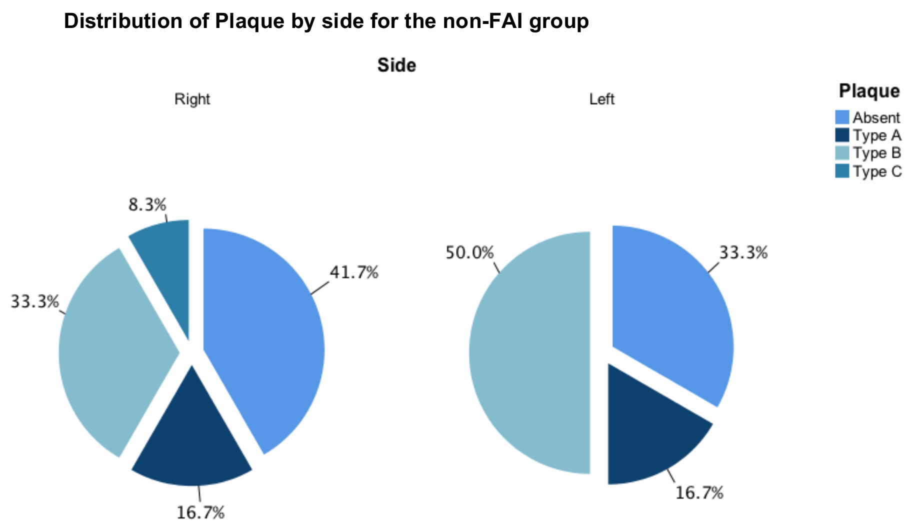


Figure 7-8 Pie charts of distribution of plaque for non-FAI sample

For the non-FAI group, plaque was present on 15 (62.5%) and absent on 9 (37.5%) femora. Type A plaque was present on 4 (16.7%) femora, 10 (41.7%) had type B and 1 (4.2%) had type C present. For the left side, type A was present on 2 femora, type B was present on 6 femora, type C was present on 0 femora. While 4 left femora were absent for plaque. For the right side, type A plaque was present on 2 femora, type B was present on 4 femora and type C was present on 1 femur. While 5 right femora did not have plaque present (see Figure 7-8).

For the FAI group, Table 7-17 shows the cross tabulation for the occurrence of plaque on the left side and right side. 33.3% (6/18) of individuals were recorded as being bilaterally absent for plaque. Type A plaque occurred bilaterally in 1/18 individuals, while neither type B and C occurred bilaterally.

Table 7-17 cross tabulation of the occurrence of plaque by left and right side, FAI group

	Type	Right side				
		A	**B**	**C**	**Absent**	**Total**
Left side	**A**	1	2	0	0	3
	B	1	0	2	1	4
	C	0	0	0	0	0
	Absent	2	2	1	6	11
	Total	4	4	3	7	18

For the non-FAI group, Table 7-18 shows the cross tabulation for the occurrence of plaque on the left side and right side. 25% (3/12) of individuals did not have plaque present on either femur, while 0% of individuals had bilateral type A plaque, 16.7% of individuals had type B on both femora and type C did not occur bilaterally.

Table 7-18 cross tabulation of the occurrence of plaque by left and right side, non-FAI group

	Type	Right side				
		A	**B**	**C**	**Absent**	**Total**
Left side	**A**	0	2	0	0	2
	B	1	2	1	2	6
	C	0	0	0	0	0
	Absent	1	0	0	3	4
	Total	2	4	1	5	12

When considering the distribution of plaque by sex for both samples combined, 52.6% of male and 59.1% of female femora had plaque present. Table 7-19 shows the distribution of plaque by sex and side.

Table 7-19 Count of femora categorised by plaque type by side and sex, FAI and non-FAI combined

Sex	**Side**	**Absent**	**Type A**	**Type B**	**Type C**	**Total**
Male	Left	10	4	5	-	19
	Right	8	4	6	1	19
	Total	**18**	**8**	**11**	**1**	**38**
Female	Left	5	1	5	-	11
	Right	4	2	2	3	11
	Total	**9**	**3**	**7**	**3**	**22**
Total		**27**	**11**	**18**	**4**	**60**

With regards to age range category and plaque, the 18-29 years age category had the highest prevalence rates of plaque followed by 50+ years and then 30-49 years. Table 7-20 presents the number of femora for each plaque category by age range category while 7-21 presents the percentage of femora with each plaque type for each age group and 7-22 presents the percentage of femora within each plaque type present by age group.

Table 7-20 Count of femora categorised for plaque type by age group, FAI and non-FAI combined

Age group	Absent	Type A	Type B	Type C	Total
18-29 years	3	2	4	1	10
30-49 years	16	5	9	2	32
50+ years	8	4	5	1	18
Total	**27**	**11**	**18**	**4**	**60**

Table 7-21 Percentage of femora within each age group category by plaque type, FAI and non-FAI combined

Age group	% of observable femora absent for Plaque within age group	% of observable femora present for Type A within age group	% of observable femora present for Type B within age group	% of observable femora present for Type C within age group
18-29 years	30.0%	20.0%	40.0%	10.0%
30-49 years	50.0%	15.6%	28.1%	6.3%
50+ years	44.4%	22.2%	27.8%	5.6%

Table 7-22 Percentage of femora within each plaque type group by age range category, FAI ang non-FAI groups combined

Age group	% of observable femora absent for Plaque between age group	% of observable femora present for Type A between age group	% of observable femora present for Type B between age group	% of observable femora present for Type C between age group
18-29 years	11.1%	18.2%	22.2%	25.0%
30-49 years	59.3%	45.5%	50.0%	50.0%
50+ years	29.6%	36.4%	27.8%	25.0%

With FAI and non-FAI was combined, to increase sample size under analysis, a one-way ANOVA was run determine if there was a significant difference in the mean age between plaque types. For the right side, there was an extreme outlier present for the type B plaque group which caused a deviation from normality (*p = 0.026*). A comparison test was run excluding this case however as it did not affect the conclusions it was maintained. For the original data mean age was highest for those without plaque (44.08 years) followed by type A (41.33 years), type B (39.38 years) and type C (38.25 years). There was no significant difference in mean age between the plaque types, $F(3,26) = 0.276$, $p = 0.842$.

For the left side, mean age was highest for femora with type A (44.80 years) present followed by type B (42.70 years) and then those without plaque present (39.60 years). There was no significant difference between the mean age and plaque type, $F(2,27) = 0.331$, $p = 0.721$.

When comparing the prevalence rates of plaque between the FAI and non-FAI groups a fisher's exact test showed no significant difference in the proportion between the two groups ($p = 0.913$) on the right side or the left side (p= 0.221).

7.3. Alpha angles and non-metric traits

In order to determine if there was a significant difference in mean alpha angle size between femora with Poirier's facets, plaque (and between type) and cribra present and those absent for these traits, independent sample t-tests and one-way ANOVAs run for each side separately, with both the FAI group and non-FAI group combined to increase sample size under analysis. This section is to determine if there is a link between any of these non-metric traits and alpha angle size.

Poirier's facets

There was a significant difference in mean alpha angle size between femora with and without Poirier's facets for both the right and left side, Table 7-23 shows the descriptive statistics. For the right side there was a significant difference in mean alpha angle size between femora with Poirier's facets present (55.59° ± 9.24°) and those absent (49.65° ± 6.01°), $t(28) = -2.102$, $p = 0.045$. The left side also showed a significant difference between those with Poirier's facets present (62.70° ± 10.72°) and those without (50.58° ± 6.25°), $t(28) = -3.856$, $p = 0.001$. Figure 7-9 shows the distribution of alpha angles between those with and without Poirier's facets.

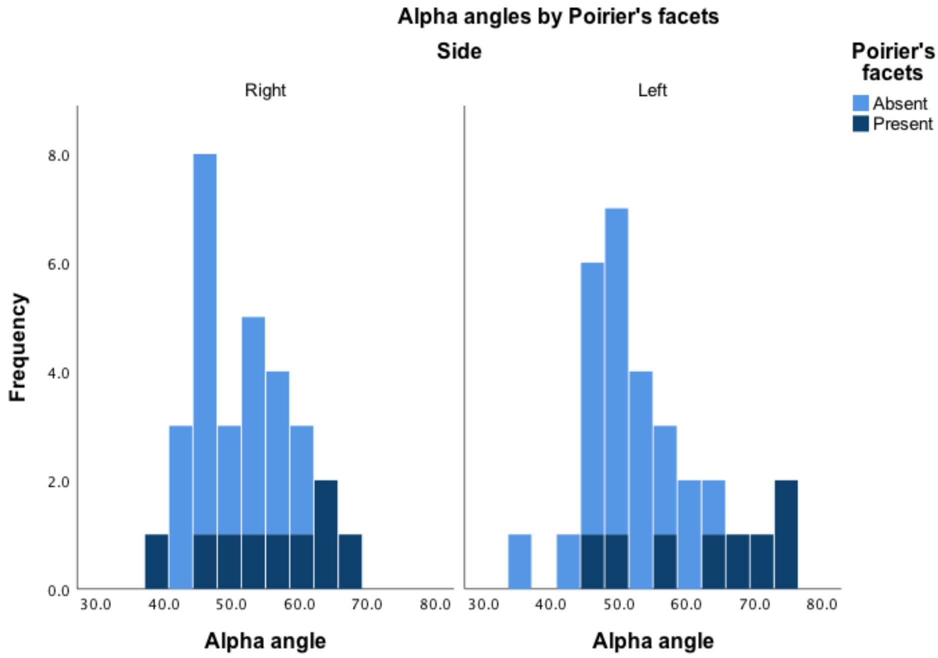


Figure 7-9 Histogram of alpha angle by the presence of Poirier's facets, pooled sex, FAI and non-FAI combined

Table 7-23 Descriptive statistics for alpha angle size when split by femoral side and presence/absence of Poirier's facets, pooled for sex, FAI and non-FAI groups combined.

	Poirier's facets	N	Mean (°)	Min. (°)	Max. (°)	Range (°)	Std. Dev.
Left Femora	Absent	22	50.45	35.55	62.82	27.27	6.28
	Present	8	62.70	47.02	74.72	27.70	10.72
Right Femora	Absent	21	49.62	40.92	60.64	19.72	6.04
	Present	9	55.59	39.46	66.64	27.18	9.24

Plaque

The descriptive statistics for alpha angle size by plaque type are shown in Table 7-24 below and the distribution of alpha angles by plaque type is shown in Figure 7-10. For the right side, alpha angle size decreased from type A (53.87° ± 5.34°) to absent for plaque (52.75° ± 9.62°) to type B (49.31° ± 4.89°) to type C (48.07° ± 7.32°). There was no statistically significant difference found between alpha angle size and plaque type $F(3, 26) = 0.802$, $p = 0.504$, $\eta^2 = 0.085$.

For the left side, there was also a decrease in mean alpha angle size from type A (55.79°± 5.25°) to absent for plaque (54.96° ± 12.08°) to type B (51.10° ± 4.95°). There was no statistically significant difference in mean alpha angle size between plaque types Welch's $F(2, 27) = 0.640$, $p = 0.535$, $\eta^2=0.045$.

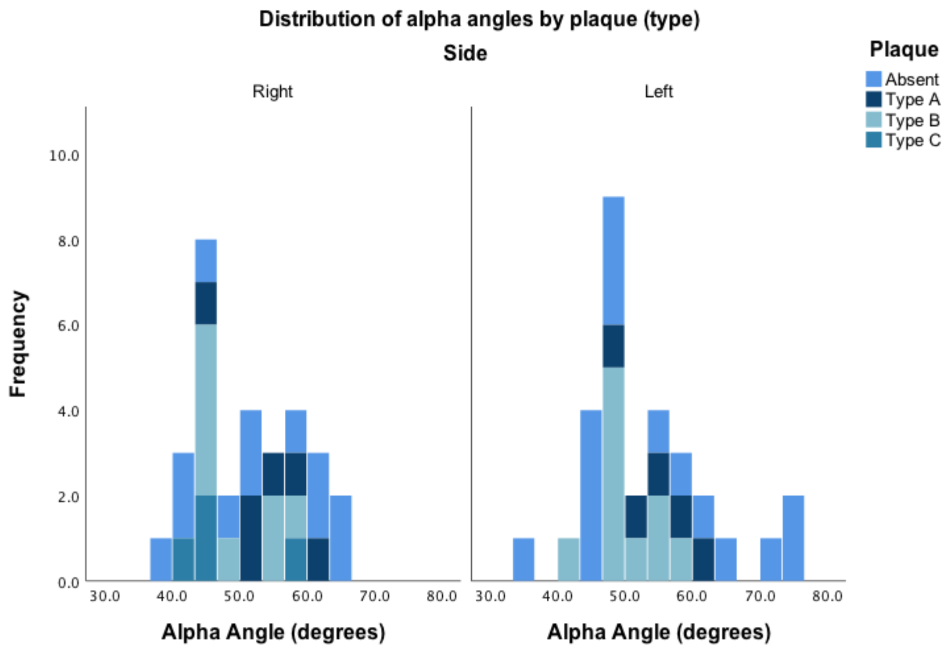


Figure 7-10 Histogram of distribution of alpha angles by the presence of plaque (by type), pooled sex, FAI and non-FAI groups combined

Table 7-24 Descriptive statistics for alpha angle size when split by femoral side and presence (by type)/absence of plaque, pooled for sex, FAI and non-FAI combined

Plaque	Side	N	Mean (°)	Std. Dev.	Std. error	Min. (°)	Max. (°)
Absent	Left	15	54.96	12.08	3.12	35.55	74.72
	Right	12	52.75	9.62	2.78	39.46	66.64
	All	27	53.98	10.91	2.10	35.55	74.72
Type A	Left	5	55.79	5.25	2.35	49.75	62.82
	Right	6	53.87	5.34	2.18	45.00	60.64
	All	11	54.74	5.13	1.55	45.00	62.82
Type B	Left	10	51.10	4.95	1.56	42.57	59.15
	Right	8	49.31	4.89	1.73	44.43	56.77
	All	18	50.31	4.86	1.15	42.57	59.15
Type C	Left	-	-	-	-	-	-
	Right	4	48.07	7.32	3.66	42.49	58.75

7.4. Cam morphology and non-metric traits

To determine if there was a difference in proportions of femora with and without non-metric traits and having cam morphology (as determined by the threshold levels of ≥50°, ≥55° and ≥60°) chi-squared tests of homogeneity and fisher's exact tests (if the sample size was <5) were performed. Analysis was performed with the FAI and non-FAI groups combined to increase sample sizes and give an overall understanding of the difference in proportions for all the modern clinical sample. Following this the FAI and non-FAI groups have been reviewed separately to determine if the presence or absence of FAI impacts the proportions of femora having cam morphology based on non-metric traits.

Poirier's facets

≥50° Threshold

The first non-metric trait to be assessed was Poirier's facets. When the FAI and non-FAI groups were combined, on the right side, there was no statistically significant difference in proportions of femora with an alpha angle ≥50° than those with an angle <50°, dependent on the presence or absence of Poirier's facets, $p = 0.118$. For the left side there was again no significant difference in the difference in proportions of femora with an alpha angle ≥50° than those with an angle <50°, between femora with Poirier's facets present or absent, $p = 0.215$. Table 7-25 shows the distribution of femora with and without Poirier's facets for femora with and without Poirier's facets.

Table 7-25 Distribution of femora with/without cam morphology (50° threshold) by Poirier's facets, pooled sex, FAI and non-FAI combined

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<50°)	57.1%(12)	22.2%(2)	46.7%(14)
	Present (≥50°)	42.9%(9)	77.8%(7)	53.3%(16)
	Total	100.0%(21)	100.0%(9)	100.0%(30)
Left	Absent (<50°)	59.1%(13)	25.0%(2)	50.0%(15)
	Present (≥50°)	40.9%(9)	75.0%(6)	50.0%(15)
	Total	100.0%(22)	100.0%(8)	100.0%(30)

For the FAI group, for the right side there was no significant difference in the proportions of femora with an alpha angle ≥50° than those with an angle <50° dependent on the presence or absence of Poirier's facets, *p = 1.000.* 71.4% of femora with Poirier's facets present and 63.6% with Poirier's facets absent had cam morphology (see Table 7-26). For the left side, there was again no significant difference in proportions of femora with or without cam morphology between those with and without Poirier's facets, *p=0.638.* 66.7% of femora with Poirier's facets present and 50.0% with Poirier's facets absent had cam morphology present (see Table 7-26).

Table 7-26 Distribution of femora with/without cam morphology (50° threshold) by Poirier's facets, FAI group, pooled sex

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<50°)	36.4%(4)	28.6%(2)	33.3%(6)
	Present (≥50°)	63.6%(7)	71.4%(5)	66.7%(12)
	Total	100.0%(11)	100.0%(7)	100.0%(18)
Left	Absent (<50°)	50.0%(6)	33.3%(2)	44.4%(8)
	Present (≥50°)	50.0%(6)	66.7%(4)	55.6%(10)
	Total	100.0%(12)	100.0%(6)	100.0%(18)

For the non-FAI group, on the right side there was no significant difference in proportions of femora with and without cam morphology based on the alpha angle threshold of ≥50° and the presence or absence of Poirier's facets, *p= 0.091.* 100.0% of femora with Poirier's facets present and 20.0% with Poirier's facets absent had an alpha angle ≥50° (see Table 7-27). For the left side there was again no significant difference, *p= 0.152.* 100.0% of femora with Poirier's facets present and 30.0% without Poirier's facets had an alpha angle ≥50°. There were, however, only two femora with Poirier's facets present on each side (see Table 7-27).

Table 7-27 Distribution of femora with/without cam morphology (50° threshold) by Poirier's facets, Non-FAI group, pooled sex

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<50°)	80.0%(8)	0.0%(0)	66.7%(8)
	Present (≥50°)	20.0%(2)	100.0%(2)	33.3%(4)
	Total	100.0%(10)	100.0%(2)	100.0%(12)
Left	Absent (<50°)	70.0%(7)	0.0% (0)	58.3%(7)
	Present (≥50°)	30.0% (3)	100.0% (2)	41.7% (5)
	Total	100.0% (10)	100.0% (2)	100.0% (12)

≥55° Threshold

At the 55° threshold level, when combining both the FAI and non-FAI groups, for the right side, there was no significant difference in proportions of femora with and without cam morphology between femora with and without Poirier's facets, *p= 0.115.* For the left side there was a significant difference in proportions of femora with and without cam morphology between those with and without Poirier's facets, *p= 0.028.* See Table 7-28 for the distribution of femora with and without cam morphology for those with and without Poirier's facets.

Table 7-28 Distribution of femora with/without cam morphology (55° threshold) by Poirier's facets, pooled sex, FAI and non-FAI groups combined

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<55°)	76.2% (16)	44.4% (4)	66.7% (20)
	Present (≥55˚)	23.8% (5)	55.6% (5)	33.3% (10)
	Total	100.0% (21)	100.0% (9)	100.0% (30)
Left	Absent (<55°)	77.3% (17)	25.0% (2)	63.3% (19)
	Present (≥55˚)	22.7% (5)	75.0% (6)	36.7% (11)
	Total	100.0% (22)	100.0% (8)	100.0% (30)

For FAI-group, on the right side there was no significant difference in proportions of femora with or without cam morphology between those with Poirier's facets present and absent, *p= 1.000*. For the left side there was also no significant difference, *p= 0.321.* See Table 7-29 for the distribution of femora between the different groups.

Table 7-29 Distribution of femora with/without cam morphology (55° threshold) by Poirier's facets, FAI-group, pooled sex

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<55°)	54.5% (6)	57.1% (4)	55.6% (10)
	Present (≥55˚)	45.5% (5)	42.9% (3)	44.4% (8)
	Total	100.0% (11)	100.0% (7)	100.0% (18)
Left	Absent (<55°)	66.7% (8)	33.3% (2)	55.6% (10)
	Present (≥55˚)	33.3% (4)	66.7% (4)	44.4% (8)
	Total	100.0% (12)	100.0% (6)	100.0% (18)

For the non-FAI group, the right side showed a significant difference in the proportions of femora with or without cam morphology between those with and without Poirier's facets present or absent, *p= 0.015*. 100% of femora with Poirier's facets present had cam morphology present, while 0% those without Poirier's facets had cam morphology present (Table 7-30). For the left side, there was also a significant difference, *p= 0.045.* 100% of femora with Poirier's facets present had cam morphology present while 10% of those without Poirier's facets had cam morphology present (Table 7-30).

Table 7-30 Distribution of femora with/without cam morphology (55° threshold) by Poirier's facets, pooled sex, non-FAI group

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<55°)	100.0% (10)	0.0% (0)	83.3% (10)
	Present (≥55˚)	0.0% (0)	100.0% (2)	16.7% (2)
	Total	100.0% (10)	100.0% (2)	100.0% (12)
Left	Absent (<55°)	90.0% (9)	0.0% (0)	75.0% (9)
	Present (≥55˚)	10.0% (1)	100.0% (2)	25.0% (3)
	Total	100.0% (10)	100.0% (2)	100.0% (12)

≥60° Threshold

At the 60° threshold, level when combining both FAI groups, on the right side there was a significant difference in proportions of femora with and without cam morphology between those with and without Poirier's facets present, *p= 0.019.* 44.4% of femora with Poirier's facets present had alpha angles ≥60° while only 4.8% of femora with Poirier's facets absent had alpha angle ≥60° (Table 7-31). For the left side there was also a statistically significant difference, *p= 0.002.* 62.5% of femora with Poirier's facets had alpha angles ≥60° while only 4.5% of femora with Poirier's facets absent had alpha angle ≥60° (Table 7-31).

Table 7-31 Distribution of femora with/without cam morphology (60° threshold) by Poirier's facets, pooled sex, FAI and non-FAI groups combined

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<60°)	95.2% (20)	55.6% (5)	83.3% (25)
	Present (≥60°)	4.8% (1)	44.4% (4)	16.7% (5)
	Total	100.0% (21)	100.0% (9)	100.0% (30)
Left	Absent (<60°)	95.5% (21)	37.5% (3)	80.0% (24)
	Present (≥60°)	4.5% (1)	62.5% (5)	20.0% (6)
	Total	100.0% (22)	100.0% (8)	100.0% (30)

For the FAI-group, for the right side there was not a statistically significant difference in the proportion of femora with and without cam morphology based on the 60° threshold, $p = 0.528$. For the left side, there was also no significant difference in proportions, $p = 0.083$. See Table 7-32 for the distribution of femora with and without cam morphology for those with and without Poirier's facets.

Table 7-32 Distribution of femora with/without cam morphology (60° threshold) by Poirier's facets, FAI-group, pooled sex

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<60°)	90.9% (10)	71.4% (5)	83.3% (15)
	Present (≥60°)	9.1% (1)	28.6% (2)	16.7% (3)
	Total	100.0% (11)	100.0% (7)	100.0% (18)
Left	Absent (<60°)	91.7% (11)	50.0% (3)	77.8% (14)
	Present (≥60°)	8.3% (1)	50.0% (3)	22.2% (4)
	Total	100.0% (12)	100.0% (6)	100.0% (18)

For the non-FAI group, there was a significant difference in the proportions of femora with cam morphology by the presence or absence of Poirier's facets on both sides, $p=0.015$ for both sides. Left and right side showed 100% of femora with Poirier's facets present and 0% of those without Poirier's facets had an alpha angle ≥60° (see Table 7-33).

Table 7-33 Distribution of femora with/without cam morphology (60° threshold) by Poirier's facets, pooled sex, Non-FAI group

Side	Cam morphology	Poirier's facets % (n)		Total
		Absent	Present	
Right	Absent (<60°)	100.0% (10)	0.0% (0)	83.3% (10)
	Present (≥60°)	0.0% (0)	100.0% (2)	16.7% (2)
	Total	100.0% (10)	100.0% (2)	100.0% (12)
Left	Absent (<60°)	100.0% (10)	100.0% (2)	83.3% (10)
	Present (≥60°)	0.0% (0)	100.0% (0)	16.7% (2)
	Total	100.0% (10)	100.0% (2)	100.0%(12)

Plaque

≥50° Threshold

When the FAI and non-FAI groups were combined, on the right side, at the 50° threshold, there was no significant difference in the proportions of femora with and without cam morphology by the type of plaque present, *p=0.269.* For the left side there was also no significant difference in proportions, *p= 0.481.* See Table 7-34 for the distribution of femora with and without cam morphology for the different types of plaque.

Table 7-34 Distribution of femora with/without cam morphology (50° threshold) by plaque, pooled sex, FAI and non-FAI groups combined.

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<50°)	41.7% (5)	16.7% (1)	62.5% (5)	75.0% (3)	46.7% (14)
	Present (≥50˚)	58.3% (7)	83.3% (5)	37.5% (3)	25.0% (1)	53.3% (16)
	Total	100.0%(12)	100.0%(6)	100.0%(8)	100.0%(4)	100.0%(30)
Left	Absent (<50°)	53.3% (8)	20.0%(1)	60.0%(6)	-	50.0% (15)
	Present (≥50˚)	46.7% (7)	80.0%(4)	40.0%(4)	-	50.0%(15)
	Total	100.0%(15)	100.0%(5)	100.0%(10)	-	100.0% (30)

For the FAI-group, both the right (*p= 0.747*) and left (*p= 0.330*) there was no significant difference in proportions. Table 7-35 shows the distribution of femora with and without cam morphology for each plaque group.

Table 7-35 Distribution of femora with/without cam morphology (50° threshold) by plaque, FAI-group, pooled sex

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<50°)	28.6%(2)	25.0%(1)	25.0%(1)	66.7%(2)	33.3%(6)
	Present (≥50˚)	71.4%(5)	75.0%(3)	75.0%(3)	33.3%(1)	66.7%(12)
	Total	100.0%(7)	100.0%(4)	100.0%(4)	100.0%(3)	100.0%(18)
Left	Absent (<50°)	54.5%(6)	0.0%(0)	50.0%(2)	-	44.4%(8)
	Present (≥50˚)	45.5%(5)	100.0%(3)	50.0%(2)	-	55.6%(10)
	Total	100.0%(11)	100.0%(3)	100.0%(4)	-	100.0%(18)

For the non-FAI group, for both the right *(p=0.107)* and the left *(p=1.000)* there was no significant difference in the proportions of femora with and without cam morphology between the different plaque types, see Table 7-36.

Table 7-36 Distribution of femora with/without cam morphology (50° threshold) by plaque, pooled sex, Non-FAI group

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<50°)	60.0%(3)	0.0%(0)	100.0%(4)	100.0%(1)	66.7%(8)
	Present (≥50˚)	40.0%(2)	100.0%(2)	0.0%(0)	0.0%(0)	33.3%(4)
	Total	100.0%(5)	100.0%(2)	100.0%(4)	100.0%(1)	100.0%(12)
Left	Absent (<50°)	50.0%(2)	50.0%(1)	66.7%(4)	-	58.3%(7)
	Present (≥50˚)	50.0%(2)	50.0%(1)	33.3%(2)	-	41.7%(5)
	Total	100.0%(4)	100.0%(2)	100.0%(6)	-	100.0%(12)

≥55° Threshold

When FAI and non-FAI groups were combined, for the right side, there was no significant difference between the proportions of femora with cam morphology and those without by those with plaque and those without, *p= 0.458.* For the left side there is also no significant difference in proportions, *p= 0.885.* The difference in proportions of femora with and without cam morphology for each plaque type is shown in Table 7-37.

Table 7-37 Distribution of femora with/without cam morphology (55° threshold) by plaque, pooled sex, FAI and non-FAI groups

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<55°)	58.3%(7)	50.0%(3)	87.5%(7)	75.0%(3)	66.7%(20)
	Present (≥55°)	41.7%(5)	50.0%(3)	12.5%(1)	25.0%(1)	33.3%(10)
	Total	100.0%(12)	100.0%(6)	100.0%(8)	100.0%(4)	100.0%(30)
Left	Absent (<55°)	60.0%(9)	60.0%(3)	70.0%(7)	-	63.3%(19)
	Present (≥55°)	40.0%(6)	40.0%(2)	30.0%(3)	-	36.7%(11)
	Total	100.0%(15)	100.0%(5)	100.0%(10)	-	100.0%(30)

For the FAI group, for both right (*p= 0.631)* and left *(p= 0.810)* sides there was no significant differences in proportions (see Table 7-38).

Table 7-38 Distribution of femora with/without cam morphology (55° threshold) by plaque, FAI group, pooled sex

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<55°)	57.1%(4)	25.0%(1)	75.0%(3)	66.7%(2)	55.6%(10)
	Present (≥55°)	42.9%(3)	75.0%(3)	25.0%(1)	33.35(1)	44.4%(8)
	Total	100.0%(7)	100.0%(4)	100.0%(4)	100.0%(3)	100.0%(18)
Left	Absent (<55°)	63.6%(7)	33.3%(1)	50.0%(2)	-	55.6%(10)
	Present (≥55°)	36.4%(4)	66.7%(2)	50.0%(2)	-	44.4%(8)
	Total	100.0%(11)	100.0%(3)	100.0%(4)	-	100.0%(18)

For the non-FAI group, for both the right *(p= 0.697)* and the left side *(p= 0.509)* there was no significant difference in the proportion of femora with and without cam morphology present between plaque types (see Table 7-39).

Table 7-39 Distribution of femora with/without cam morphology (55° threshold) by plaque, non-FAI sample, pooled sex

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<55°)	60.0%(3)	100.0%(2)	100.0%(4)	100.0%(1)	83.3%(10)
	Present (≥55°)	40.0%(2)	0.0%(0)	0.0%(0)	0.0%(0)	16.7%(2)
	Total	100.0%(5)	100.0%(2)	100.0%(4)	100.0%(1)	100.0%(12)
Left	Absent (<55°)	50.0%(2)	100.0%(2)	83.3%(5)	-	75.0%(9)
	Present (≥55°)	50.0%(2)	0.0%(0)	16.7%(1)	-	25.0%(3)
	Total	100.0%(4)	100.0%(2)	100.0%(6)	-	100.0%(12)

≥60° Threshold

When the FAI and non-FAI groups were combined both the right (*p*= *0.210*) and left side (*p*= *0.110*) showed no significant difference in the proportions of femora with cam morphology dependent on the plaque type present (or absent), see Table 7-40.

Table 7-40 Distribution of femora with/without cam morphology (60° threshold) by plaque, pooled sex, FAI and non-FAI combined

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<60°)	66.7%(8)	83.3%(5)	100.0%(8)	100.0%(4)	83.3%(25)
	Present (≥60°)	33.3%(4)	16.7%(1)	0.0%(0)	0.0%(0)	16.7%(5)
	Total	100.0%(12)	100.0%(6)	100.0%(8)	100.0%(4)	100.0%(30)
Left	Absent (<60°)	66.7%(10)	80.0%(4)	100.0%(10)	-	80.0%(24)
	Present (≥60°)	33.3%(5)	20.0%(1)	0.0%(0)	-	20.0%(6)
	Total	100.0%(15)	100.0%(5)	100.0%(10)	-	100.0%(30)

For the FAI group, both right (*p= 0.863)* and left *(p= 0.569)* sides showed no significant difference in proportions of femora with and without cam morphology by plaque type, see table 7-41 for the distribution of femora for each group.

Table 7-41 Distribution of femora with/without cam morphology (60° threshold) by plaque, pooled sex, FAI group

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<60°)	71.4%(5)	75.0%(3)	100.0%(4)	100.0%(3)	83.3%(15)
	Present (≥60°)	28.6%(2)	25.0%(1)	0.0%(0)	0.0%(0)	16.7%(3)
	Total	100.0%(7)	100.0%(4)	100.0%(4)	100.0%(3)	100.0%(18)
Left	Absent (<60°)	72.7%(8)	66.7%(2)	100.0%(4)	-	77.8%(14)
	Present (≥60°)	27.3%(3)	33.3%(1)	0.0%(0)	-	22.2%(4)
	Total	100.0%(11)	100.0%(3)	100.0%(4)	-	100.0%(18)

For the non-FAI group, both right *(p= 0.697)* and the left side *(p= 0.106)* showed there was no significant difference in the proportions of femora with and without cam morphology between different plaque types, see Table 7-42.

Table 7-42 Distribution of femora with/without cam morphology (60° threshold) by plaque, pooled sex, Non-FAI groups

Side	Cam morphology	Plaque % (n)				Total
		Absent	Type A	Type B	Type C	
Right	Absent (<60°)	60.0%(3)	100.0%(2)	100.0%(4)	100.0%(1)	83.3%(10)
	Present (≥60°)	40.0%(2)	0.0%(0)	0.0%(0)	0.0%(0)	16.7%(2)
	Total	100.0%(5)	100.0%(2)	100.0%(4)	100.0%(1)	100.0%(12)
Left	Absent (<60°)	50.0%(2)	100.0%(2)	100.0%(6)	-	83.3%(10)
	Present (≥60°)	50.0%(2)	0.0%(0)	0.0%(0)	-	16.7%(2)
	Total	100.0%(4)	100.0%(2)	100.0%(6)	-	100.0%(12)

Chapter 8. Results IIII: Skeletal collection data compared & combined

In this chapter the results of the statistical analysis of the males from the Wharram Percy and the Luís Lopes collection will be compared to determine any significant differences between the two collections.

In section 8.1.1 alpha angle size will be compared to determine if there is a significant difference between the two samples. The distribution of age will also be compared to determine if there is a difference in age distribution and if this had a significant impact on the difference in alpha angle size between the two samples.

8.1.2. focuses on the distribution of non-metric traits to determine if there is a significant difference between the two collections.

8.2. will compare the occupation data including the LLC occupations and the WPC. This is to determine if there is a significant difference between alpha angle size between the occupations, the occupational activity categories and the WPC data.

8.3. will combine the data for the WPC and LLC to allow further statistical tests to be carried out which require larger sample sizes than were available for the collections separately, such as binary regression. It allows further understanding of the association between cam morphology and non-metric traits without being limited to a particular sample.

8.4. Is focused on the osteitis pubis data. Comparing alpha angle size between those with and without each trait and also dependent on the number of osteitis pubis traits present. Analysis will also be performed controlled for age to identify if any differences are due to age.

8.5. is focused on additional findings which were identified during the recording process, this includes herniation pits.

8.1. Skeletal collection data compared

8.1.1. Alpha angle data

The mean alpha angle size for the Wharram Percy collection males (n = 112) was 53.62° ± 11.39°, while for the Luís Lopes collection it was 54.18° ± 10.99° (see Table 8-1 for the descriptive statistics). For the left side there was no significant difference in mean alpha angle between the two collections, $t(162) = -0.033$, $p = 0.974$ and for the right side the mean alpha angle size was also not statistically significantly different, $t(153) = -0.610$, $p = 0.543$, based on independent t-tests (see Table 8-2).

Table 8-1 Descriptive statistics for alpha angle size by collection, WPC & LLC compared

Collection	Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
Wharram Percy	Right	53	47.67	31.68	79.35	52.48	10.90
	Left	59	50.70	31.94	82.63	54.64	11.81
	All	112	50.96	31.68	82.63	53.62	11.39
Luís Lopes collection	Right	102	45.97	34.15	80.12	53.64	11.32
	Left	105	43.34	33.63	76.97	54.70	10.69
	All	207	46.49	33.63	80.12	54.18	10.99

Table 8-2 Independent sample t-test data table for alpha angle by skeletal collection for left and right side

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	-0.033	162	0.974	-0.059	1.807	-3.627	3.508
Right side	-0.610	153	0.543	-1.155	1.893	-4.894	2.584

Distribution of age

There was a significant difference in the proportions of individuals per age range category between the two collections as determined by a chi-squared test of homogeneity, $p = 0.050$. For the Wharram Percy collection, 22.2% of individuals were in the 18-29 years category, 38.9% were in the 30-49 years category and 38.9% were in the 50+ years category. While for the Luís Lopes collection 12.0% were in the 18-29 years category, 29.6% were in 30-49 years category and 58.3% were in the 50+ years category.

Alpha angle size controlled for age

Due to the differences in age distribution between the two collections a two-way ANOVA was run in order to determine if the distribution of age impacted the alpha angle size when comparing the two collections.

For the right side, the alpha angle data for Wharram Percy 30-49 years group (*p = 0.027)* and Luís Lopes collection, 50+ years group (*p = 0.004*) was not normally distributed, as assessed by a Shapiro-Wilks test, therefore a comparison test was run using transformed data. The comparison test using transformed data showed no difference in conclusions to the original data test. It was not however possible to correct for the violation of normality for the 50+ years group but the sample size was >30, the original data was therefore used for this test. For the original data there was no statistically significant interaction between age range category and skeletal collection on alpha angle, $F(2, 140)= 0.276$, $p = 0.759$. partial $\eta^2= 0.004$. There was also no significant difference in alpha angle size between age range categories $F(2, 140)= 1.783$, $p = 0.172$, partial $\eta^2= 0.025$ or skeletal collection $F(2,140)= 0.881$, $p = 0.881$, partial $\eta^2= <0.0005$. Figure 8-1 shows the estimated marginal means of alpha angles by age range categories for both collections.

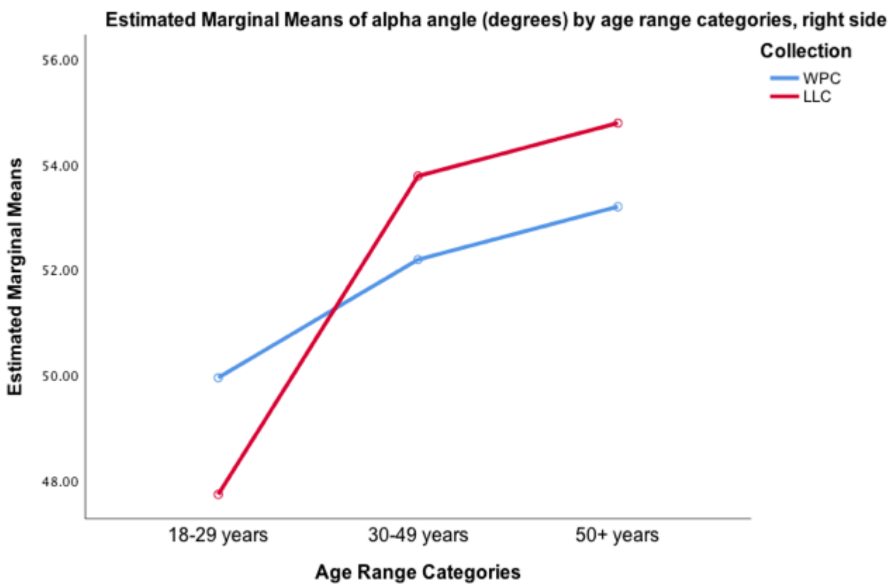


Figure 8-1 Estimated marginal means plot for alpha angles by age range categories for each collection, right side

For the left side there was an extreme outlier present for the Wharram Percy, 18-29 years group and the data was not normally distributed for the Luís Lopes collection 30-49 years group (*p = 0.015*) and 50+ years (*p= 0.049*) groups, therefore comparison tests were run to determine if the violations of these test assumptions would impact the conclusions. The comparison test with transformed data showed the same conclusions as the original data therefore the original data was used. For the original data there was no significant interaction between age range category and skeletal collection on alpha angle size, $F(2,145)= 0.372$, $p= 0.690$, partial $\eta^2= 0.005$. There was also no significant difference in alpha angle size between collections, $F(2, 145)= 0.010$, $p = 0.921$ partial $\eta^2= <0.0005$. There was however a significant difference in alpha angle size between age range categories, $F(2,145)= 5.423$, $p = 0.005$, partial $\eta^2= 0.070$. The alpha angle size increased from 18-29 years (47.76° ± 2.16) [mean ± Std. Error], to 30-49 years (54.48° ± 1.57) to 50+ years (56.15° ± 1.38). The mean alpha angle for the 30-49 years group was 6.72°± 2.67° higher than the 18-29 years group. Additionally, the 50+ years group was 8.39°± 2.56° higher than the 18-29 years group. Only the difference between 50+ years and 18-29 years (*p= 0.004*) was statistically significant when adjusted for Bonferroni's correction (p = 0.016667), see Figure 8-2 for the estimated marginal means plot of alpha angles by age range category for both collections.

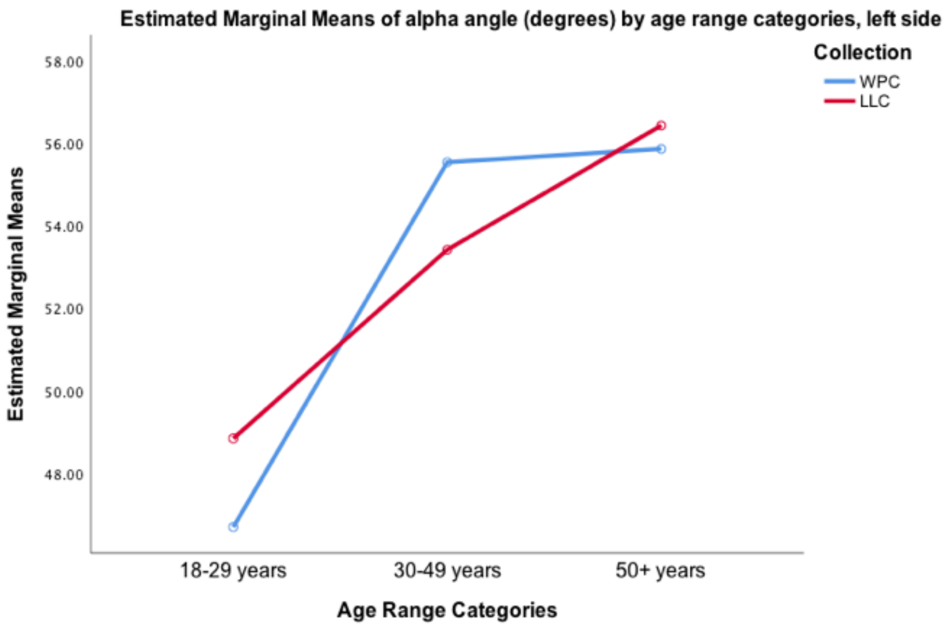


Figure 8-2 Estimated marginal means plot for alpha angles by age range categories for each collection, left side

8.1.2. Non-metric traits

To determine if there was a significant difference in the proportions of non-metric traits between the two collections chi-squared test of homogeneity and fisher's exact test were run. There was only a significant difference for plaque type A between the two collections.

Poirier's facets

The distribution of Poirier's facets was extremely similar for both collections by side as shown in Figure 8-3 below.

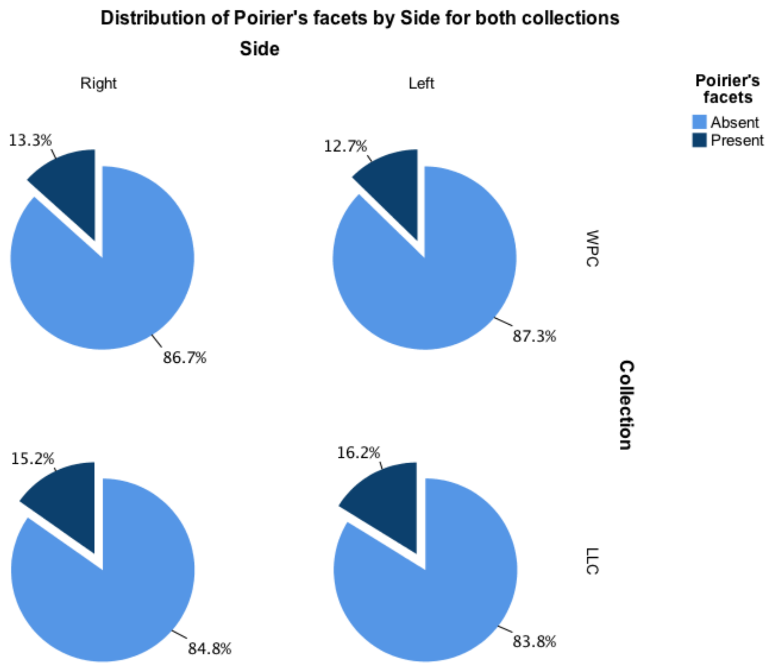


Figure 8-3 Distribution of Poirier's facets by collection

A chi-squared test of homogeneity was run to determine if there was a difference in proportions of femora with Poirier's facets present/absent between the two collections. For the right and left sides, there was no significant differences in the proportions of femora with Poirier's facets absent/present between the two collections, $p = 0.739$ and $p = 0.538$ respectively.

Plaque

The distribution of plaque was again similar between the two collections, as shown in Figure 8-4. For both sides the Wharram Percy collection had a larger prevalence of femora with type A plaque present than the Luís Lopes collection. The Luís Lopes collection however had a larger prevalence of femora with type B present than the Wharram Percy collection.

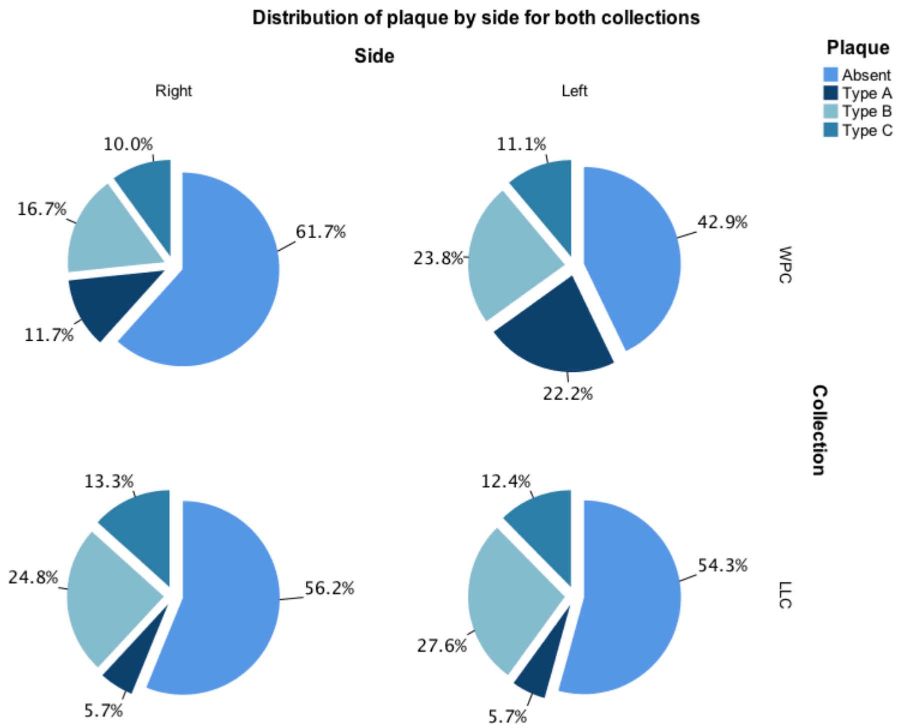


Figure 8-4 Distribution of plaque by collection

For the right side a fisher's exact test was run to determine if there was a difference in proportions of femora with plaque (by type) absent/present between the two collections. There was no statistically significant difference in proportions, *p= 0.343.*

Using a chi-squared test of homogeneity for the left side there was a statistically significant difference in proportions, $\chi^2(3) = 10.313$, *p= 0.016.* Pairwise comparison post hoc test using multiple z-tests of two proportions with a Bonferroni correction ($p < 0.0125$) showed only the proportions of femora with type A plaque was different between collections, *p = 0.001.*

Cribra

The distribution of femora with cribra present (by type) was lower for the Luís Lopes collection in comparison to the Wharram Percy collection, see Figure 8-5. There were very few femora with type II cribra present for both collections however this was particularly lower for the Luís Lopes collection.

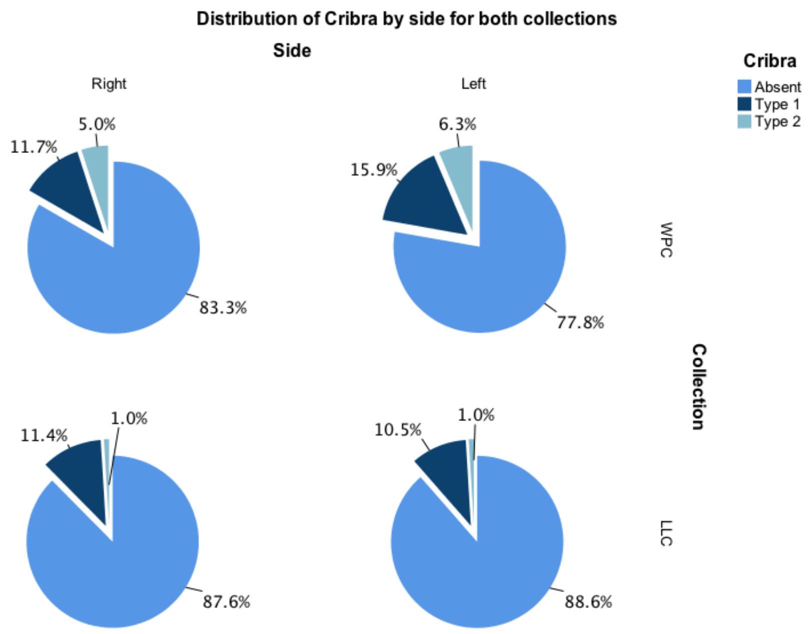


Figure 8-5 Distribution of cribra by collection

For the right side using a fisher's exact test there was no significant difference in the proportions of femora with cribra (by type) absent/present between the collections, *p= 0.302.* While for the left side there was also no significant difference in proportions between collections, *p= 0.063.*

8.2. Alpha angles and occupations

There was no significant difference in mean alpha angle size between the Wharram Percy collection, the individual ISCO-08 occupations and each occupation activity category for all three methods used. The results of each one-way ANOVA are shown below.

There was no significant difference in mean alpha angle size, on the right side, between the ISCO-08 categories and the Wharram Percy sample, $F(8,146)=0.954$, $p= 0.475$. The mean alpha angle size was highest for the elementary occupation group and lowest for the undetermined category. The alpha angle data for the clerical support worker and undetermined categories were not normally distributed and it was not possible to transform the data to reach normality therefore a non-parametric comparison test was run. The Kruskal-Wallis test showed no significant difference between each category, $\chi^2(8)= 6.692$, $p = 0.570$. For the left side, there was no significant difference in mean alpha angle size between categories, $F(8,155)=0.786$, *p= 0.615.* The data for the Craft and Related Trades Workers was not normally distributed however n>30. The comparison test did not however affect conclusions therefore the untransformed data was used. Figure 8-6 shows the spread of data for each of the occupation categories including the Wharram Percy collection.

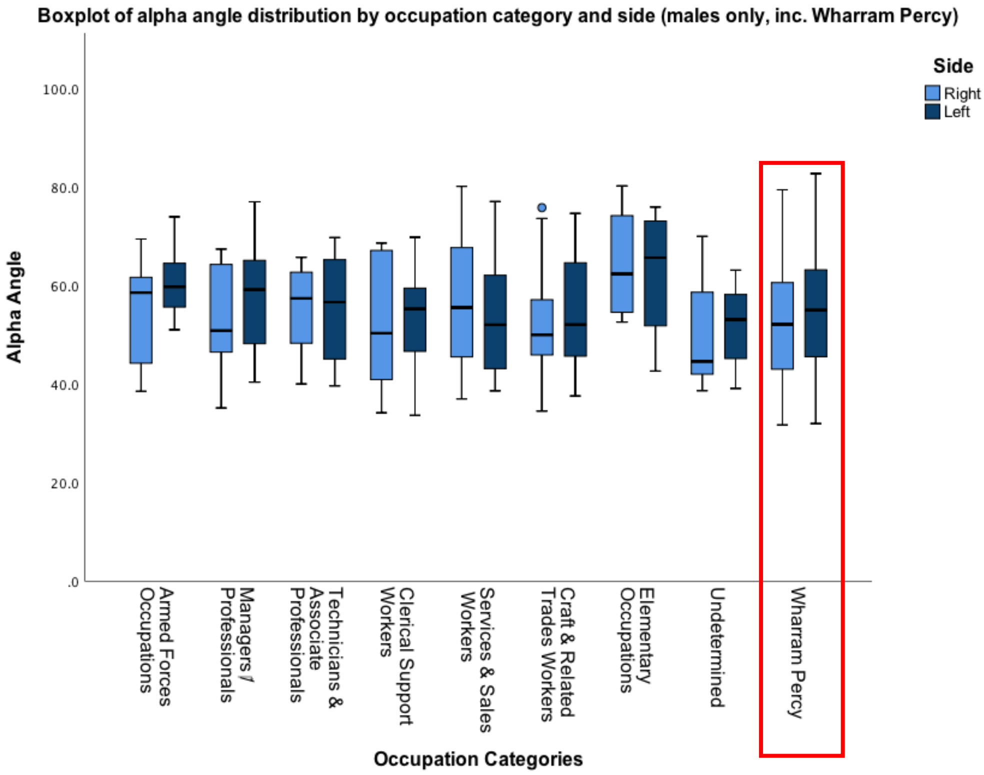


Figure 8-6 Boxplot of alpha angle size by ISCO-08 occupation categories and the Wharram Percy males

For method I, on the right side the Wharram Percy mean alpha angle size is the lowest out of all categories (see Figure 8-7). There was however no significant difference in mean alpha angle size between each category, *F(3,132)= 0.744, p=0.528.* The alpha angle data was not normally distributed for the low activity group, therefore a non-parametric comparison test was run, as it was not possible to transform the data to reach normality. A Kruskal-Wallis test also showed no significant difference, $\chi^2(3)= 1.554$, *p= 0.670.* For the left side, there was no significant difference in mean alpha angle size between each category, *F(3,142)=0.186, p= 0.906,* however on this side the Wharram Percy data was second highest, between low activity and high activity categories. The alpha angle data was not normally distributed for the high activity category however n>30. It was not possible to transform this data to reach normality therefore a Kruskal-Wallis non-parametric test was run. This also showed no significant difference in the median alpha angle size between each category, *$\chi^2(3)$= 0.420, p = 0.936.*

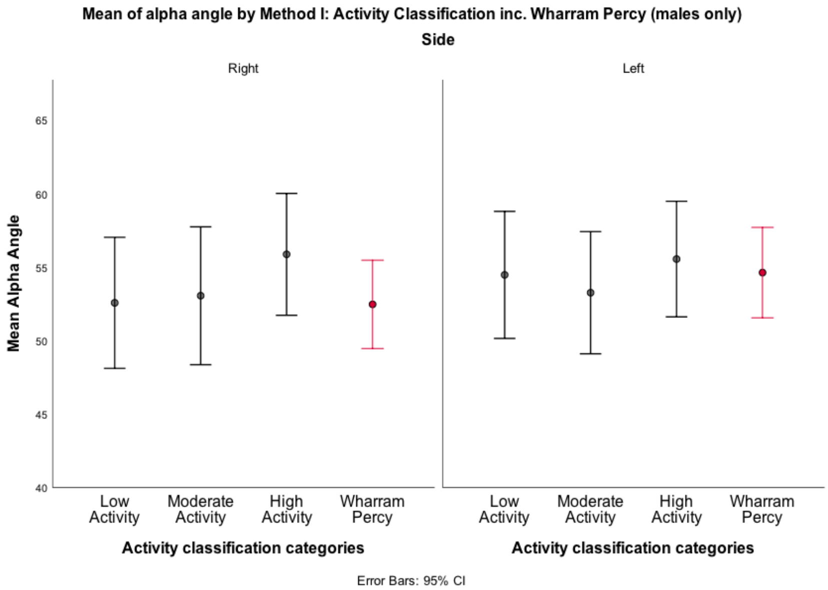


Figure 8-7 Mean alpha angle size between method I: activity classification method including Wharram Percy males

For method II, on the right side there was no significant difference in mean alpha angle size between each category, *F(3,132)= 0.759, p= 0.519.* The alpha angle data was not normally distributed for the sedentary behaviour group therefore a non-parametric comparison test was therefore run as it was not possible to reach normality through transforming the data. The Kruskal-Wallis test showed no significant difference in median alpha angle size between each category, *$\chi^2(3)$= 1.590, p = 0.662.* For the left side, the mean alpha angle data for the Wharram Percy sample was the second highest after moderate intensity (see Figure 8-8). There was no significant difference in mean alpha angle between each category, *F(3,142)=0.168, p= 0.918.* The alpha angle data was not normally distributed for the moderate intensity group however n>30. It was not possible to transform this data therefore a non-parametric comparison test was run. The Kruskal-Wallis test showed no significant difference in median alpha angle size between each category, *$\chi^2(3)$= 0.389, p = 0.943.*

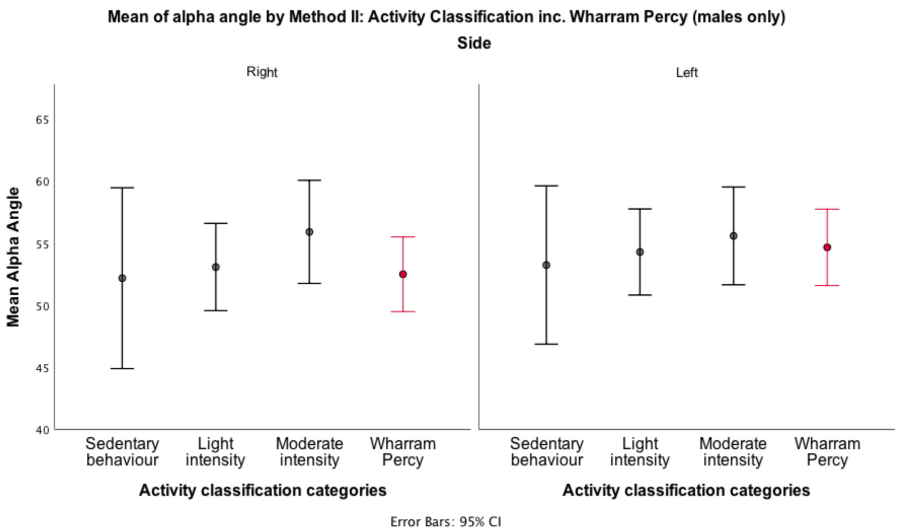


Figure 8-8 Mean alpha angle size between method II: activity classification method including Wharram Percy males

For method III, on the right side the Wharram Percy mean alpha angle data was less than the Luís Lopes collection data when categorised as manual and non-manual (see Figure 8-9). This difference was however not significant, *F(2,140)= 0.202, p= 0.818.* For the left side, the mean alpha angle size was highest for the Wharram Percy data. There was no significant difference in alpha angle size between all categorise, *F(2,149)= 0.105, p= 0.900.* The alpha angle data for the manual category was not normally distributed however n>30. A comparison test with the alpha angle data transformed to reach normality showed no difference in conclusions.

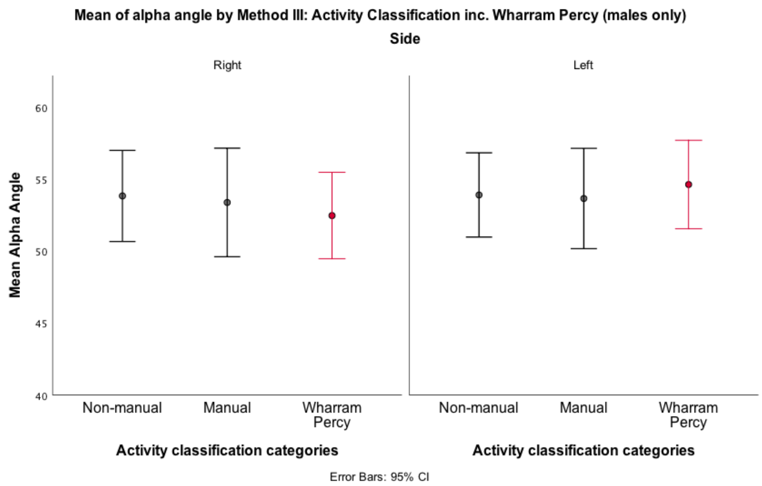


Figure 8-9 Mean alpha angle size between method III: activity classification method including Wharram Percy males

8.3. Skeletal collection data combined

8.3.1. Regression analysis

Binary logistic regression was performed to determine if it was possible to predict the presence of cam morphology (at each threshold level) using the absence/presence of Poirier's facets and plaque (by type). Additionally, due to the significant difference in alpha angle size between femora with and without Poirier's facets, for both samples, binary regression was also used to determine if alpha angle and offset data could predict the presence or absence of this trait.

Cam morphology thresholds

≥50˚ threshold

For the left side there was one standardised residual with a value of -4.629, therefore a comparison test was run with and without this outlier. When the outlier was included the logistic regression model was statistically significant $\chi^2(4) = 33.111$, $p = <0.0005$. The overall percentage accuracy in classification was 65.2%. The model sensitivity was 64.5%, specificity was 66.2%, positive predictive value was 72.3% and negative predictive value was 57.7%. Of the 6 variables in the equation only three were statistically significant, Poirier's facets (0.003) and plaque A (0.022) (see Table 8-3).

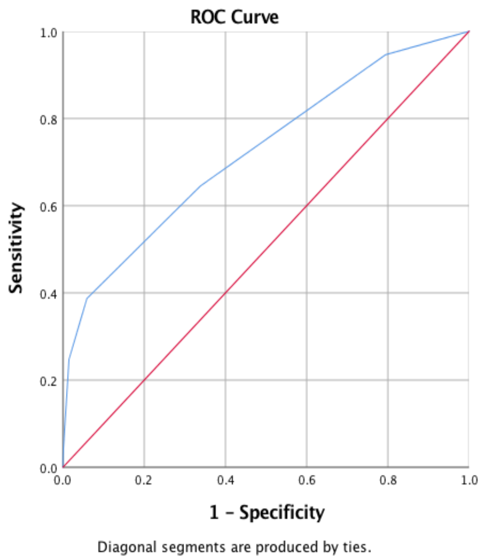


Figure 8-10 ROC Curve for prediction of femur with alpha angle ≥50˚, left

The area under the ROC (Receiver Operating Characteristics) curve (Figure 8-10) was 0.723 (95% CI 0.646 to 0.800), which is acceptable discrimination.

When the outlier was excluded the overall accuracy in classification increased marginally to 65.6%, the model sensitivity remained at 64.5% however the specificity increased to 67.2%. The positive predictive value increased to 73.2% while the negative predictive value remained the same. Poirier's facets were no longer statistically significant, Poirier's facets (p=0.998) but type A plaque remained significantly (p= 0.023). There was no reason however to exclude this point.

Table 8-3 Table of logistic regression predicted likelihood of alpha angle ≥50˚ based on Poirier's facets and plaque, left side only

	B	SE	Wald	df	p	Odds ratio	95% CI for Odds ratio	
							lower	Upper
Poirier's facet	3.168	1.054	9.029	1	0.003	23.755	3.009	187.540
Plaque			9.941	3	0.019			
Plaque A	1.577	0.690	5.226	1	0.022	4.842	1.252	18.719
Plaque B	0.337	0.403	0.699	1	0.403	1.400	0.636	3.083
Plaque C	-0.927	0.583	2.530	1	0.112	0.396	0.126	1.240
Constant	-0.103	0.261	0.157	1	0.692	0.902		

For the right side the logistic regression model was statistically significant $\chi^2(4) = 36.769$, $p = <0.0005$. The overall percentage accuracy in classification was 65.4%. The model sensitivity was 57.8%, specificity was 76.2%, positive predictive value was 77.6% and negative predictive value was 55.2%. Of the 6 variables in the equation only one was statistically significant, plaque A (p= 0.040), see Table 8-4.

The area under the ROC curve (Figure 8-11) was 0.729 (95% CI 0.651 to 0.807), which is acceptable discrimination.

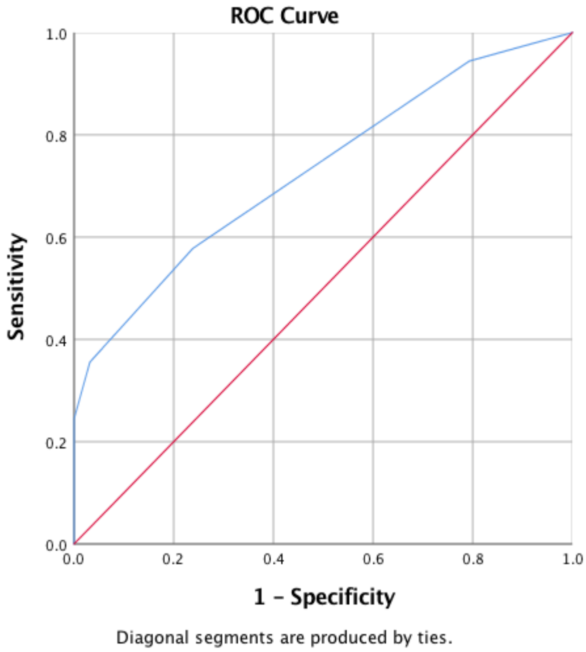


Figure 8-11 ROC Curve for prediction of femur with alpha angle ≥50˚, right side only

Table 8-4 Table of logistic regression predicted likelihood of alpha angle ≥50˚ based on Poirier's facets and plaque, right side only

	B	SE	Wald	df	p	Odds ratio	95% CI for Odds ratio	
							lower	Upper
Poirier's facet	21.222	8551.656	0.000	1	0.998	1.646E+9	0.000	
Plaque			9.047	3	0.029			
Plaque A	1.668	0.812	4.224	1	0.040	5.303	1.080	26.029
Plaque B	0.490	0.431	1.290	1	0.256	1/632	0.701	3.798
Plaque C	-0.897	0.579	2.394	1	0.122	0.408	0.131	1.270
Constant	-0.059	0.243	0.059	1	0.808	0.943		

≥55˚ threshold

For the left side the logistic regression model was statistically significant $\chi^2(4) = 27.120,\ p = <0.0005$. The overall percentage accuracy in classification was 66.5%. The model sensitivity was 41.0%, specificity was 90.4%, positive predictive value was 80% and negative predictive value was 62.0%. Of the 6 variables in the equation only three were statistically significant, Poirier's facets (p=0.001) and plaque overall (p=0.015) but only plaque A within the category (p=0.009), see Table 8-5.

The area under the ROC curve was 0.708 (95% CI 0.628 to 0.788), which is acceptable discrimination, see Figure 8-12.

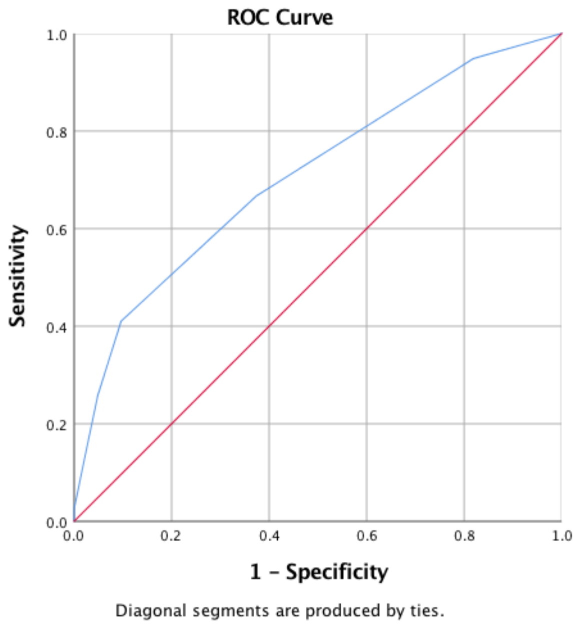


Figure 8-12 ROC Curve for prediction of femur with alpha angle ≥55˚, left side only

Table 8-5 Table of logistic regression predicted likelihood of alpha angle ≥55˚ based on Poirier's facets and plaque, left side only

	B	SE	Wald	df	p	Odds ratio	95% CI for Odds ratio	
							lower	Upper
Poirier's facet	2.054	.610	11.335	1	.001	7.802	2.359	25.798
Plaque			10.485	3	.015			
Plaque A	1.651	.631	6.846	1	.009	5.213	1.513	17.956
Plaque B	.386	.407	.899	1	.343	1.471	.662	3.266
Plaque C	-.796	.624	1.630	1	.202	.451	.133	1.531
Constant	-.526	.269	3.827	1	.050	.591		

For the right side the logistic regression model was also statistically significant $\chi^2(4)$ = *54.117, p = <0.0005.* The overall percentage accuracy in classification was 73.2%. The model sensitivity was 68.6%, specificity was 77.1%, positive predictive value was 71.6% and negative predictive value was 74.4%. Of the 6 variables in the equation, plaque type A (p=0.003) and B (p=0.015) and constant (p = <0.0005), see Table 8-6.

The area under the ROC curve was 0.777 (95% CI 0.701 to 0.853), which is acceptable discrimination, see Figure 8-13.

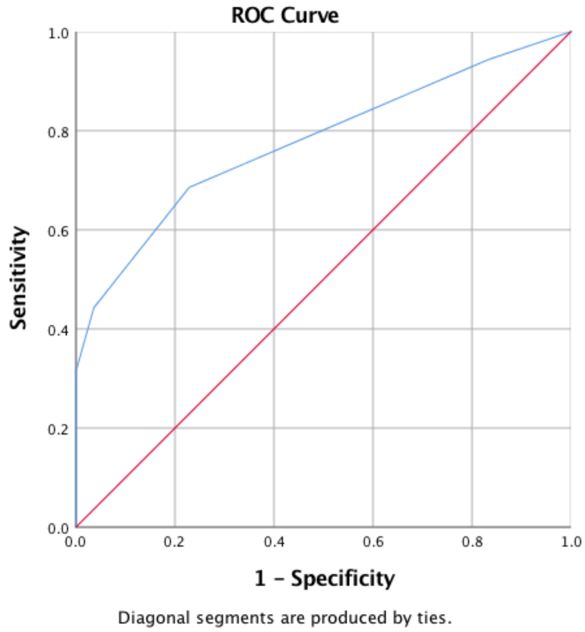


Figure 8-13 ROC Curve for prediction of femur with alpha angle ≥55˚, right side only

Table 8-6 Table of logistic regression predicted likelihood of alpha angle ≥55˚ based on Poirier's facets and plaque, right side only

	B	SE	Wald	df	p	Odds ratio	95% CI for Odds ratio	
							lower	Upper
Poirier's facet	22.146	8496.463	.000	1	.998	4146434791.673	.000	.
Plaque			13.666	3	.003			
Plaque A	2.120	.721	8.645	1	.003	8.333	2.028	34.248
Plaque B	1.082	.444	5.949	1	.015	2.951	1.237	7.042
Plaque C	-.231	.630	.135	1	.714	.794	.231	2.729
Constant	-1.022	.275	13.815	1	.000	.360		

≥60˚ threshold

For the left side, the logistic regression model was statistically significant $\chi^2(4) = 34.573$, *p* = <0.0005. The overall percentage accuracy in classification was 75.8%. The model sensitivity was 50.9%, specificity was 89.4%, positive predictive value was 72.5% and negative predictive value was 76.9%. Of the 6 variables in the equation only, Poirier's facets (p=<0.0005) and plaque overall (p=0.003) but only plaque A within category (p=<0.0005) and constant (p=<0.005) were statistically significant, see Table 8-7.

The area under the ROC curve was 0.740 (95% CI 0.656 to 0.824), which is acceptable discrimination, see Figure 8-14.

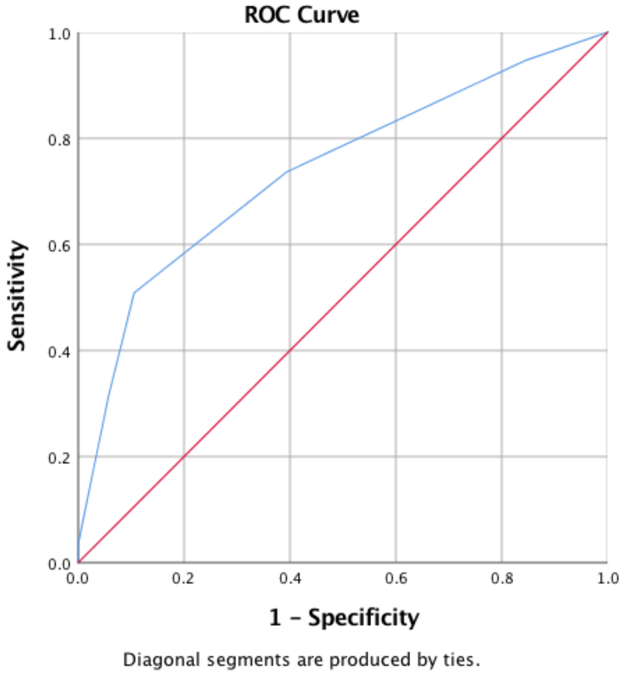


Figure 8-14 ROC Curve for prediction of femur with alpha angle ≥60˚, left side only

Table 8-7 Table of logistic regression predicted likelihood of alpha angle ≥60˚ based on Poirier's facets and plaque, left side only

	B	SE	Wald	df	p	Odds ratio	95% CI for Odds ratio	
							lower	Upper
Poirier's facet	2.373	.573	17.164	1	.000	10.726	3.491	32.956
Plaque			14.025	3	.003			
Plaque A	2.185	.622	12.338	1	.000	8.893	2.627	30.103
Plaque B	.537	.463	1.346	1	.246	1.711	.690	4.243
Plaque C	-.300	.707	.180	1	.671	.741	.185	2.962
Constant	-1.374	.323	18.085	1	.000	.253		

For the right side, the logistic regression model was also statistically significant, $\chi^2(4) = 39.085$, *p = <0.0005.* The overall percentage accuracy in classification was 79.1%. The model sensitivity was 52.1%, specificity was 91.4%, positive predictive value was 73.5% and negative predictive value was 80.7%. Of the 6 variables in the equation, Poirier's facets (*p = <0.0005*), and plaque overall (*p = 0.017*) but only plaque A within category (*p = 0.002*) and constant (*p = <0.005*), see Table 8-8.

The area under the ROC curve was 0.765 (95% CI 0.677 to 0.853), which is acceptable discrimination, see Figure 8-15.

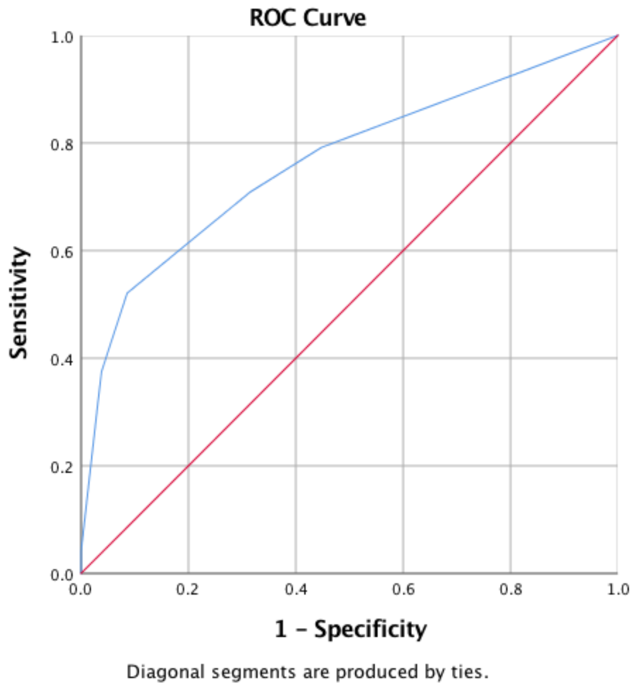


Figure 8-15 ROC Curve for prediction of femur with alpha angle ≥60˚, right side only

Table 8-8 Table of logistic regression predicted likelihood of alpha angle ≥60˚ based on Poirier's facets and plaque, right side only

	B	SE	Wald	df	p	Odds ratio	95% CI for Odds ratio	
							lower	Upper
Poirier's facet	3.226	.643	25.199	1	.000	25.169	7.144	88.682
Plaque			10.178	3	.017			
Plaque A	2.116	.678	9.742	1	.002	8.301	2.198	31.355
Plaque B	.827	.509	2.646	1	.104	2.287	.844	6.199
Plaque C	.527	.662	.634	1	.426	1.694	.463	6.202
Constant	-1.780	.342	27.099	1	.000	.169		

Non-metric traits

Poirier's facets

A binary linear regression was carried to determine the effect of the alpha angle size, age range category and offset ratio on the likelihood of Poirier's facet being present. For the left side, the logistic regression model was statistically significant $\chi^2(6) = 29.891$, $p = <0.0005$. The overall percentage accuracy in classification was 88.4%. The model sensitivity was 23.5%, specificity was 97.5%, positive predictive value was 57.1% and the negative predictive value was 90.1%. Of the variables in the equation alpha angle ($p = 0.001$) and constant ($p = <0.0005$) were statistically significant, see Table 8-9.

Table 8-9 Table of logistic regression predicted likelihood of Poirier's facets based on alpha angle, offset ratio and age range category, left side only

	B	SE	Wald	df	Sig.	Exp(B)	95% CI for Odds ratio	
							Lower	Upper
Age range categories			0.375	2	0.829			
Age range category (1)	-0.007	1.224	0.000	1	0.996	0.994	0.090	10.949
Age range category (2)	0.375	1.142	0.108	1	0.743	1.455	0.155	13.646
Alpha angle	0.120	0.035	11.650	1	0.001	1.128	1.052	1.208
Offset ratio	-0.267	0.850	0.099	1	0.753	0.766	0.145	4.049
Constant	-8.991	2.529	12.645	1	0.000	0.000		

The area under the ROC curve was 0.822 (95% CI 0.734 to 0.910), which is excellent level of discrimination, see Figure 8-16.

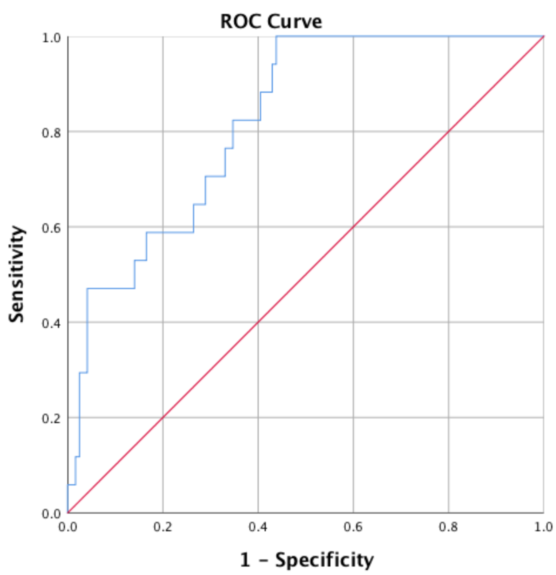


Figure 8-16 ROC Curve for Poirier's facets, males and left side only

For the right side, the logistic regression model was statistically significant $\chi^2(6) = 44.121$, $p = <0.0005$. The overall percentage accuracy in classification was 86.9%. The model sensitivity was 31.6%, specificity was 95.8%, positive predictive value was 54.5% and the negative predictive value was 89.7%. Of the variables in the equation only alpha angle ($p = <0.0005$) and constant ($p = <0.0005$) were statistically significant, see Table 8-10.

Table 8-10 Table of logistic regression predicted likelihood of Poirier's facets based on alpha angle, offset ratio and age range category, right side only

							95% CI for Odds ratio	
	B	SE	Wald	df	Sig.	Exp(B)	Lower	Upper
Age range categories			0.336	2	0.845			
Age range category (1)	0.378	1.311	0.083	1	0.773	1.460	0.112	19.066
Age range category (2)	0.633	1.252	0.256	1	0.613	1.884	0.162	21.928
Alpha angle	0.186	0.043	18.893	1	0.000	1.205	1.108	1.311
Offset ratio	-0.955	0.933	1.048	1	0.306	0.385	0.062	2.395
Constant	-12.499	3.016	17.170	1	0.000	0.000		

The area under the ROC curve was 0.915 (95% CI 0.866 to 0.963), which is excellent level of discrimination, see Figure 8-17.

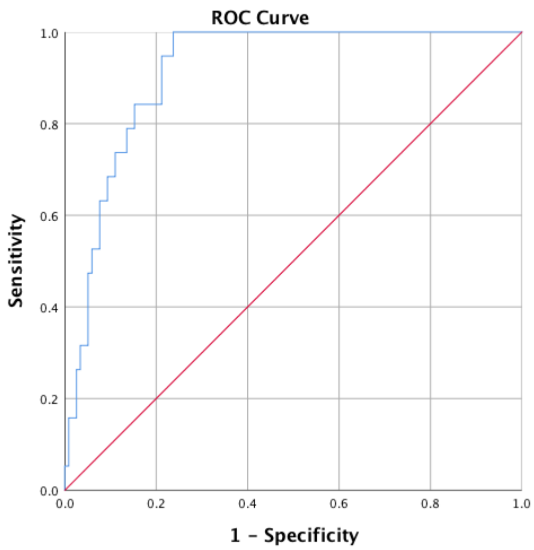


Figure 8-17 ROC Curve, Poirier's facets for males and right side only

8.4. Osteitis pubis analysis

The osteitis pubis recording criteria included; erosions, porosity, irregularity, osteophytes and eburnation. When the Wharram Percy and Luís Lopes collections (including all individuals from both collections) were combined, to determine if there was a link between each osteitis pubis trait and alpha angle size, Mann-Whitney U tests were run. Due to the known impact age has on the pubic symphysial face it was important to control for age when analysing these traits. In order to establish if there was a significant interaction between age range category and the number of osteitis pubis traits present, when determining if there is a significant difference in alpha angle size, two-way ANOVAs were run. This was carried out for both symphysial and femoral side.

Due to the presence of exact age data for the Luís Lopes collection one-way ANCOVAs were run to determine if, after adjusting for age, there was a significant difference in mean alpha angle size between individuals with and without each of the osteitis pubis traits. Additionally, one-way ANCOVAs were run to determine if after adjusting for age there was a significant difference in alpha angle size between individuals with 0, 1, 2, 3 or 4 osteitis pubis criteria present.

Wharram Percy and Luís Lopes collection

When the osteitis pubis data was combined, due to the violation of normality for several traits which were unable to be transformed to reach normality, Mann-Whitney U tests were used to determine if there was a significant difference in alpha angle size dependent on the presence or absence of each of the osteitis pubis traits. The only traits which showed a significant difference in median alpha angle size were erosions and irregularity (as shown in Table 8-11 below), with those with the traits present having a higher alpha angle size than those without the trait. Only one right pubic symphysis and three left pubic symphysis had eburnation present. Therefore, eburnation was excluded from analyses.

Table 8-11 Mann-Whitney U p-values for alpha angle size by osteitis pubis traits

Pubic symphysis side	Osteitis pubis trait	Sig.	
		Right femur alpha angles	Left femur alpha angles
Left	Erosions	0.005*	0.002*
	Porosity	0.192	0.579
	Irregularity	0.398	0.042*
	Osteophytes	0.533	0.315
Right	Erosions	0.323	0.028*
	Porosity	0.699	0.809
	Irregularity	0.216	0.439
	Osteophytes	0.817	0.796

Two-way ANOVAs were run to determine if there was a significant interaction between age range category and the number of osteitis pubis criteria recorded on the pubic symphysis, on mean alpha angle size. No pubic symphysis had all five traits present. There was not a significant interaction effect between age range category and the number of osteitis pubis criteria on the left pubic symphysis on alpha angle size for the left femur, see Table 8-12. However, the data for one osteitis pubis criteria present in the 30-49 years group was not normally distributed (p=0.007). It was not possible to transform this to reach normality.

Table 8-12 Two-way ANOVA data table for number of osteitis pubis criteria on the left side and left alpha angle size

Left alpha angle			
Source	df	Sig.	Partial Eta Squared
Age range categories	2	0.144	0.043
Left side, number of osteitis pubis criteria	4	0.430	0.042
Age range category * osteitis pubis criteria	6	0.057	0.126

There was also no significant interaction effect between age range category and the number of osteitis pubis criteria present on the right pubic symphysis on alpha angle size on the left femur ($p = 0.932$), see Table 8-13. Again, the data for one OP criteria present in the 30-49 years group was also not normally distributed and could not be transformed to reach normality.

Table 8-13 Two-way ANOVA data table for number of osteitis pubis criteria on the right side and left alpha angle size

Left alpha angle			
Source	df	Sig.	Partial Eta Squared
Age range categories	2	0.007	0.105
Right side, number of osteitis pubis criteria	4	0.772	0.020
Age range category * osteitis pubis criteria	7	0.932	0.026

There was also no significant interaction effect between age range category and the number of osteitis pubis criteria (on the left or right pubic symphysis) on alpha angle size for the right femur, see Table 8-14. There was also no significant difference in alpha angle size between the number of osteitis pubic criteria recorded, see Table 8-15. On the right, osteitis pubis criteria for several of the variables, was not normally distributed and could not be transformed to reach normality.

Table 8-14 Two-way ANOVA data table for number of osteitis pubis criteria on the left side and right alpha angle size

Right alpha angle			
Source	df	Sig.	Partial Eta Squared
Age range categories	2	0.125	0.047
Left side, number of osteitis pubis criteria	4	0.680	0.031
Age range category * osteitis pubis criteria	6	0.44	0.064

Table 8-15 Two-way ANOVA data table for number of osteitis pubis criteria on the right side and right alpha angle size

Right alpha angle			
Source	df	Sig.	Partial Eta Squared
Age range categories	2	0.095	0.053
Right Osteitis pubis criteria	4	0.863	0.015
Age range category * osteitis pubis criteria	7	0.942	0.026

All pubic symphyses with eburnation present were from the Luís Lopes collection. No pubic symphysis from the Wharram Percy collection had eburnation recorded. All those with eburnation present also had an alpha angle >55° on one of their femora. Table 8-16 below provide additional information regarding these cases.

Table 8-16 Cases with eburnation present on pubic symphysis

	Eburnation	Other features	Alpha angle
(1)	Left & right	Right pubis symphysis: Porosity, erosions Left pubic symphysis: Porosity, erosions	Right: 67.0° Left: 69.7°
(2)	Left	Right pubic symphysis: Osteophytes, erosions Left pubic symphysis: erosions	Right: 44.9° Left: 59.2°
(3)	Left	Right pubic symphysis: Erosions Left pubic symphysis: osteophytes	Right: 62.1° Left: NR

Luis Lopes collection only

One-way ANCOVAs were run to determine if, after adjusting for age, there was a significant difference in mean alpha angle size between individuals with and without each trait, see Table 8-17. After adjusting for age, there was no significant difference in mean alpha angle size on the right femur dependent on the absence or presence of any of the osteitis pubis traits on right pubic symphysis or left pubic symphysis. It was however not possible to test for erosions on the either pubic symphysis or irregularity on the left pubic symphysis as the assumption of homogeneity of regressions was not met.

After adjusting for age, there was also no significant difference in mean alpha angle size on the left femora dependent on the absence or presence of any of the osteitis pubis traits on the right or left pubic symphyses. It was however not possible to test for erosions and porosity on the left pubic symphysis as the assumption of homogeneity of regression was not met. In addition to this, the homogeneity of variances was not met for the osteophytes on the left pubic symphysis data ($p= 0.025$) or the right pubic symphysis ($p= 0.019$) and when comparison tests were run it was not possible to transform the data to meet this assumption. The standardised residuals were not normally distributed for the right pubic symphysis with irregularity present (*p= 0.015*) however it was not possible to transform this data to reach normality.

Table 8-17 Level of significance of alpha angle size between osteitis pubis traits after adjusting for age, LLC

Pubic symphysis side	Osteitis pubis trait	Sig.	
		Right femur alpha angles	Left femur alpha angles
Left	Erosions	-	-
	Porosity	0.385	-
	Irregularity	-	0.995
	Osteophytes	0.531	0.354
Right	Erosions	-	0.335
	Porosity	0.539	0.282
	Irregularity	0.634	0.303
	Osteophytes	0.628	0.282

One-way ANCOVAs were run to determine if, after adjusting for age, there was a significant difference in mean alpha angle size for each femora between individuals with 1, 2, 3, or 4 osteitis pubis criteria present on the left or right pubic symphysis, see Table 8-18. For the right femur, after adjusting for age there was no significant difference in mean alpha angle size between individuals with 1, 2, 3 or 4 osteitis pubis criteria present on the right pubic symphysis. The standardised residuals alpha angles were not normally distributed for femora with no osteitis pubis traits present (p=0.047), it was not however possible to transform data to reach normality. There was also no significant difference in alpha angle size on the right pubic symphysis between individuals with 1, 2, 3 or 4 osteitis pubis traits on the left pubic symphysis. Again, the standardised residuals for alpha angles were not normally distributed for femora with no traits present (p=0.021), it was however not possible to transform the data to reach normality.

For the left femur, after adjusting for age there was no significant difference in mean alpha angle size between individuals with 1, 2, 3 or 4 osteitis pubis criteria present on the right pubic symphysis. The standardised residuals alpha angles were not normally distributed for femora with 3 osteitis pubis traits present (p=0.023), it was not however possible to transform data to reach normality. For the left pubic symphysis, there was again no significant difference in mean alpha angle size dependent on the number of traits present. The standardised residuals alpha angles were not normally distributed for femora with 1 osteitis pubis traits present (p=0.015), it was not however possible to transform data to reach normality

Table 8-18 One-way ANCOVA p-values of the difference in alpha angle size dependent on the number of osteitis pubis traits present, controlled for age

Pubic symphysis side	Sig.	
	Right femur alpha angles	Left femur alpha angles
Right	0.954	0.788
Left	0.148	0.618

8.5. Possible herniation pits

During analysis of both skeletal collections and 3D CT models pitted areas were noted which did not meet the descriptions provided by Radi et al. (2013)'s recording criteria for cribra, Figure 8-18 shows cribra from Radi et al. (2013)'s article while Figure 8-19 shows an example of these pitted areas from the Luís Lopes collection. It is possible these pits could be related to herniation pits. Herniation pits are typically diagnosed through the use of pelvic radiographs, appearing as cyst-like lesion at the anterosuperior aspect of the femoral neck by the epiphysis, visible as radiolucency with a sclerotic margin. They typically measuring between 3-15 mm (Tannast et al., 2007). In some of the femora observed these pits punctured through the cortical bone, while others appeared as indentations, typically found on the surface of the Poirier's facet or plaque.

For the Luís Lopes collection, only four individuals showed such pits, including four left femora and two right femora. While for the Wharram Percy collection thirteen individuals had possible herniation pits present, twelve on the left femora and seven on the right femora. When side is pooled for both collections, mean alpha angle size was marginally higher for femora with herniation pits than without as shown in table 8-20 below.

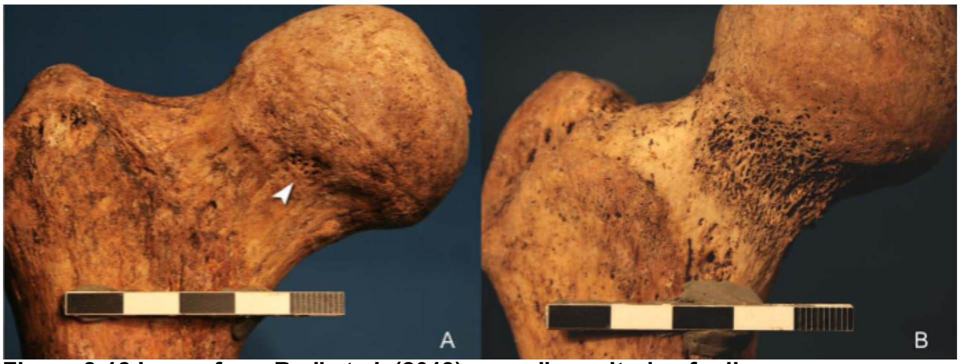


Figure 8-18 Image from Radi et al. (2013) recording criteria of cribra

Figure 8-19 Herniation pits, No 310 Luís Lopes Anthropological Collection, MUHNAC. (Photograph by E. Saunders © ULisboa-MUHNAC)

There was no significant difference in mean alpha angle size between femora with and without herniation pits for the Wharram Percy collection, as shown in Table 8-19 below.

Table 8-19 Independent sample t-test result for alpha angle size by herniation pits for Wharram Percy collection

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	0.197	86	0.845	0.776	3.945	-7.066	8.619
Right side	-0.671	81	0.504	-3.163	4.716	-12.546	6.220

Table 8-20 Descriptive statistics for alpha angle size by the presence/absence of herniation pits

Collection	Herniation pit	Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
Wharram Percy	Absent	Right	77	50.72	28.63	79.35	49.76	10.87
		Left	77	50.15	31.93	82.09	52.52	12.19
		All	154	53.46	28.63	82.09	51.14	11.59
	Present	Right	6	41.44	37.75	79.19	52.93	14.44
		Left	11	47.07	35.57	82.63	51.74	12.64
		All	17	47.07	35.57	82.63	52.16	12.86
Luís Lopes Collection	Absent	Right	99	45.97	34.15	80.12	53.59	11.41
		Left	100	43.34	33.63	76.97	54.63	10.76
		All	199	46.49	33.63	80.12	54.11	11.07
	Present	Right	2	12.14	45.19	57.33	51.26	8.59
		Left	4	26.10	43.55	69.65	56.32	11.80
		All	6	26.10	43.55	69.65	54.63	10.26

For the Luís Lopes collection there was only two femora with herniation pits present on the right side therefore it was not possible to run statistical analysis. For the left side there was no significant difference in alpha angle size between femora with and without herniation pits present (Table 8-21).

Table 8-21 Independent sample t-test result for alpha angle size by herniation pits for Wharram Percy collection

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Left side	-0.306	102	0.760	-1.685	5.503	-12.601	9.230

Possible herniation pits were seen on 3 femora from the FAI group and 4 femora from the non-FAI group. For both the FAI group and the non-FAI group the mean alpha angle size was higher for femora with herniation pits present than absent. It was not possible to run statistical analysis to determine if there was a significant difference in alpha angle size between femora with and without herniation pits present for the FAI group and the non-FAI on the left side due to the small number of femora with the pits present. For the non-FAI group was Welch's t-test was used as homogeneity of variances was not met for the right side. There was no significant difference in mean alpha angle size between femora with and without herniation pits present as shown in Table 8-22 below.

Table 8-22 Independent sample t-test result for alpha angle size by herniation pits for non-FAI

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Right side	-1.614	3.370	0.195	-8.575	5.312	-24.477	7.327

When the FAI and non-FAI groups were combined there was a significant difference in mean alpha angle size between femora with and with herniation pits present on the right side (see Table 8-23). It was not however possible to test for the left side due to the small number of femora with herniation pits present on this side. Table 8-24 shows the descriptive statistics for alpha angles between femora with and without herniation pits for the FAI and non-FAI groups.

Table 8-23 Independent sample t-test result for alpha angle size by herniation pits for non-FAI and FAI groups combined

	t-test for Equality of Means						
						95% confidence interval	
	t	df	Sig. (2-tailed)	Mean difference	Std. Error difference	Lower	Upper
Right side	-2.230	28	0.028	-7.411	3.195	-13.956	-0.866

Table 8-24 Descriptive statistics for alpha angle size between femora with and without herniation pits for the FAI and non-FAI groups

Group	Herniation pit	Side	N	Range (°)	Min. (°)	Max. (°)	Mean (°)	Std. Dev.
FAI	Absent	Right	16	21.90	39.46	61.36	51.50	7.03
		Left	17	39.17	35.55	74.72	54.07	10.01
		All	33	39.17	35.55	74.72	52.82	8.66
	Present	Right	2	10.73	55.91	10.73	61.28	7.59
		Left	1	-	-	-	-	-
		All	3	10.73	55.91	66.64	61.79	5.44
Non-FAI	Absent	Right	8	11.40	40.92	52.32	46.80	3.59
		Left	12	31.28	42.57	73.84	52.46	8.56

		All	20	32.92	40.92	73.84	50.20	7.43
	Present	Right	4	21.73	42.05	63.79	55.37	10.32
		Left	0	-	-	-	-	-
		All	4	21.73	42.05	63.79	55.37	10.32

Chapter 9. Discussion & Conclusion

The overall purpose of this research was to analyse femoroacetabular impingement and cam morphology within the context of bioarchaeology and forensic anthropology. FAI is currently not widely studied within these contexts however, with physical activity repeatedly being suggested to play a key aetiological role in cam morphology, the proposed links with non-metric traits of the femur and association with osteitis pubis, a condition which impacts the pubic symphysis (an area widely used for age estimation), further understanding within these disciplines would be of great value. Additionally, the identification and recording of this condition on skeletal remains would enables its use as an additional identifying feature in forensic investigation if ante-mortem data of FAI is present.

The four main research aims were therefore:

- To determine if there is a link between non-metric traits of the anterior aspect of the femur and cam morphology
- To explore if there is a link between cam morphology and occupational activity
- To determine if there are any osseous differences between those with FAI and asymptomatic controls
- To determine if there is a link between cam morphology and osteitis pubis

In this chapter the results of this study will be discussed under each of the main research questions. In the conclusion, an overview of the findings will be provided as well as study limitations and future work.

9.1. Is there is a link between non-metric traits of the anterior aspect of the femur & cam morphology?

Links between non-metric traits of the anterior aspect of the femur (particularly Poirier's facets, plaque type A and type B) with alpha angle size and cam morphology have been found in this study. Previous authors have hypothesised this link (Villotte and Knüsel, 2009; Radi et al., 2013) due to the similarities in location of these features, but only the current study and that by Lawrence et al. (2018) have analysed this further. This link between cam morphology and these non-metric traits can allow further understanding of each research area through collaborative discussion from the two disciplines. Here the possible links between these non-metric traits of the anterior aspect of the femur and cam morphology will be explored to identify possible associated factors.

Both non-metric traits of the anterior aspect of the femur and cam morphology have been associated with physical activity. Poirier's facets were described by Stirland (1996) as "a function of increased male muscle function." Further studies have also linked Poirier's facets to muscle function and therefore physical activity, for instance; Trinkaus (1975) suggested Poirier's facets are due to habitual flexion and abduction due to the pressure from the M. iliopsoas or pressure from the M. rectus femoris tendons. While Angel (1964) hypothesised that they are caused by pressure and friction from the iliopsoas muscle which is due to vigorous muscle functions. The significant difference in mean alpha angle size between those with and without Poirier's facets, and the use of alpha angles to predict the presence of Poirier's facets, agrees with these previous studies that Poirier's facets may be associated with physical activity. This is due to athletes typically having higher mean alpha angle sizes in comparison to non-athletic controls (Ayeni et al., 2014; Lahner et al., 2014a; Siebenrock et al., 2011) and, therefore, they could be a good indicator of physical activity (Table 9-1).

Stirland (1996) believed plaque and Allen's fossa to be more "age-related phenomena". This agrees with the findings in the current study for cribra due to its lack of association with alpha angle size but with age, for both the Wharram Percy or Luís Lopes collection collections. Conversely, other studies have suggested a link between cribra (or Allen's fossa) and physical activity (Angel, 1964; Odgers, 1931). Odgers (1931) suggested Poirier's facets develop as protection against friction from the medial part of the zona orbicularis during extension and when this protection breaks down there is the development of a depression or eroded area (Allen's fossa). The higher rates of cribra in younger individuals and the lack of association between age and Poirier's facets suggests that it is unlikely cribra is due to the breakdown of Poirier's facets.

The focus of much of the previous literature regarding non-metric traits has been on cribra and Poirier's facets, while plaque is not commonly discussed. This may be due to plaque being included with Poirier's facets and not as a separate trait in some of the early research due to their similarity in location. Re-analysis of skeletal collections included in previous studies using methods which combined these traits may allow reinterpretation of the suggested aetiologies. Angel (1964) theorised plaque forms over cribra since the prevalence is higher in modern Americans compared to the ancient Greeks, with the Americans living to more advanced ages. Stirland (1996) also found plaque to be more common on older adults than younger adults. Although Finnegan (1978) and Lawrence (2018) reported no association between plaque and age. In the current study, there was a significant interaction between plaque type and age-range category on alpha angle size for the Wharram Percy collection on the right side only but not for the Luís Lopes collection. For the Wharram Percy sample, when pooled for sex, the mean alpha angle size for those with type B plaque present was significantly higher for those in the 18-29 years group compared to the 50+ years group. Although this is likely to be due to only one femora with type B plaque present in the 18-29 years group and therefore it is difficult to determine if this a true reflection. This is not the case for the Luís Lopes collection with no significant interaction between plaque type and age range category on alpha angle size. The Luís Lopes collection and clinical CT samples (FAI-group and non-FAI group) showed no significant difference in age (using continuous exact age data) between plaque groups. It is therefore unlikely plaque is a progression of cribra with age but caused by other factors. With plaque type A and B having a significant impact on predicting the presence of cam morphology at certain thresholds (type A at all thresholds and type B at 55° threshold) this suggests, like Poirier's facets, these forms of plaque could be associated with physical activity. In addition to this, for all samples type A had the highest alpha angle size and type C had the lowest, which was significant for the Wharram Percy and Luís Lopes collection on the left side between certain plaque groups. There was also a significant difference in the proportions of femora with cam morphology present between different plaque types for the Wharram Percy on both sides but for the Luís Lopes collection this was only seen on the left side. If alpha angle size and cam morphology are associated with physical activity the results of this study suggest femora with type A and type B plaque present are more likely to have cam morphology and therefore be more physically activity than those with femora without plaque and type C.

Table 9-1 Comparison of mean alpha angle size between the current study and previous literature

Study	Sample	Sex	Alpha angle: Mean ± S.D. Total
Current study	Luís Lopes collection	Males only	54.2° ± 10.99°
	Wharram Percy	Males & Females	51.3° ± 11.62°
		Males only	53.6° ± 11.39°
	FAI Patients	Males & females	53.7° ± 8.69°
		Males only	54.5° ± 8.60°
	Controls	Males & females	51.1° ± 7.96°
		Males only	53.2° ± 9.16°
Lahner et al. (2014a)	Elite track & field athletes	Males & females	52.2° ± 7.29°
	Controls	Males & females	48.1° ± 5.45°
Gerhardt et al. (2012)	Elite soccer players	Males	65.6°
		females	52.9°
Larson et al. (2017)	Professional ice hockey players	NR	52.2° ± 11.2° (AP)
			61.0° ± 10.1° (Dunn lat.)
Ayeni et al. (2014)	Elite ice hockey players	NR	54.2° ± 12.0°
	Non-athlete controls		43.2° ± 9.7°
Lahner et al. (2014b)	Semi-professional soccer players	NR	57.3° ± 8.2°
	Amateur soccer players		51.7° ± 4.8°
Fraser et al. (2017)	Dance athletes	Females	49.5° ± 6.0°
	Non-dance athletes	Females	53.9° ± 7.3°
Mariconda et al. (2014)	Capoeira (Brazilian material arts) players	Males & females	50.7° ± 7.7° (AP)
			57.4° ± 7.1° (Frog-leg lat.)
Jung et al. (2011)	Random sample of asymptomatic individuals	Males	59.12°
		Females	45.47°
Scheidt et al. (2014)	Random sample of asymptomatic individuals	Males & females	45° ± 8.6°
		Males	47.52°
		Females	43.85°
Pollard et al. (2010a)	Asymptomatic individuals	Males	48° ± 8°
		Females	47° ± 8°

The overall alpha angle size for all samples in the current study are higher than have been reported in previous studies for non-athletic asymptomatic individuals (Pollard et al., 2010a) and nearer to the values recorded for athletes (see Table 9-1). Lawrence et al. (2018) suggested differences seen in both the mean alpha angle size and rates of Poirier's facets and plaque, between males and females, were due to physical activity differences resulting from the sexual division of labour and habitual activities. Angel (1964) also found Poirier's facets to be more common in males than females which they attributed to more vigorous muscle function in males. While Finnegan (1978) did not find a significant difference between males and females for Poirier's facets, plaque or Allen's fossa. For the Wharram Percy collection it was not possible to determine if there was an interaction effect between Poirier's facets and sex on alpha angle size due to only two female femora with Poirier's facets present however the mean alpha angle size was significantly higher for males compared to females. Although it was not possible to run the statistical analysis this difference in alpha angle size between males and females could be linked to the lower rates of Poirier's facets in females compared to males (2.9% vs 13%). The differing rates of non-metric traits and alpha angle size between sexes could be due to differing levels of physical activity or differing activities but also it could be due to morphological differences, this will be discussed in more detail in Section 9.2.

It has also been proposed that alpha angle size between athletes and non-athletes are similar, with athletes being more likely to become symptomatic due to more vigorous movements at the joint (Johnson et al., 2012). In their study of an early human hunter-gatherer population, Moats and colleagues found cam morphology was not present (using a >50° alpha angle threshold). If alpha angle size is an indicator of physical activity, this result is unexpected as it is believed the Libben population were very active in comparison to modern populations, for example, carrying out activities such as heavy lifting and walking to find food (Moats et al., 2015). It is possible that this reflects the differences in activity between this population and modern athletes, with the hunter gatherers performing less intensive but prolonged periods of strenuous activity such as; hiking with heavy loads rather than short bursts of intense activity. Conversely, it may indicate, as suggested by Johnson et al. (2012), alpha angle size is not related to physical activity. Moats et al. (2015) suggested cam morphology was a 'product of modern living' however a possible case was identified in skeletal remains of a male from the Neolithic Age (Zurmühle et al., 2017) and in the contemporaneous cemeteries at the Early Christian site of Kulubnarti, Nubia by Lawrence et al. (2018). It is therefore possible that the lack of cam morphology in the Libben population is due to differences in activity patterns or other factors, such as terrain, diet or further femoral head-neck morphology which will be discussed further.

There was not a significant difference in the proportions of Poirier's facets or alpha angle size between the males of the Wharram Percy and the males of the Luís Lopes collection. A mutual factor between these two samples, and therefore a possible contributing cause in the association between alpha angle size and Poirier's facets, is terrain. Lisbon is known as the city of seven hills (Rodrigues et al., 2011). It has irregular topography with many hills and valleys of varying sizes. The altitude ranges from 6m to 226m (Oliveira and Pinho, 2010). Acosta et al. (2017) classified the terrain of Lisbon as rugged based on the altimetry profile. While Wharram Percy is located in the Yorkshire Wolds, situated on the western side of the valley, approximately 150m above sea level (Mays, 1995; Harding and Wrathmell, 2007). Moats et al. (2015) and Lawrence et al. (2018) are currently the only other studies to have measured alpha angles on archaeological populations. In their study of the Libben population, Moats and colleagues found cam morphology was not present (using a >50° alpha angle threshold). While Lawrence et al. (2018) analysed the presence of cam morphology in contemporaneous cemeteries at Kulubnarti, Nubia, reporting it to be present in 29.9% of individuals (using a >50° threshold). In comparison to both the terrain in Lisbon and Wharram Percy, the Libben site was much flatter. The Libben site is in north-western Ohio on what was formally the Great Black Swamp. During the 8^{th}-11^{th} centuries AD, the site was occupied by the individuals studied by Moat et al. (2015), it was within a "dense elm-ash, swamp forest, covering freshwater marshes and streams…" (Meindl et al., 2008). While the Sudanese Nubian site of Kulubnarti, located in the area known as the *Batn el Hajar* ("belly of rock"), between the second and third cataracts of the River Nile (Lawrence et al., 2018), is a harsh and rugged environment. There were areas of alluvial soil by the river's edge however this was at the bottom of steep-sided slopes with rocky outcrops (Kilgore et al., 1997).

The differences in topography between the sites maybe a prominent factor for the differences in alpha angle size and cam morphology. Walking on a flat surface compared to up and down hills requires different biomechanics of the lower limb and postural adjustments. Various studies have demonstrated changes in muscle action, gait and posture in relation to walking uphill, downhill and on level surfaces (Prentice et al., 2004; Franz and Kram, 2011; Franz et al., 2012; McIntosh et al., 2006; Vrieling et al., 2008; Montgomery and Grabowski, 2018; Kawamura et al., 1991; Kang et al., 2002). When compared to walking on a level surface, additional muscle action is required to adjust the centre of mass during hill walking (Franz and Kram, 2011). During uphill walking the hip, knee and ankle extensor muscles have been found to have increased activation while for downhill walking it is only knee extensor muscles

(Lay et al., 2007; Franz and Kram, 2011). Pickle et al. (2016) showed during slope walking muscle functional roles varies from when walking on level ground due to the altered biomechanical demand. In addition to this, postural adaptation to walking on inclined surfaces occurs to reduce displacement of the centre of gravity (Leroux et al., 2002). During uphill walking Leroux and colleagues showed the trunk and pelvic alignment to be tilted more forward and a backward tilt was shown during downhill walking. Increasing treadmill grade caused increasingly flexed posture of the hip, knee and ankle, with forward tilt of the pelvis and trunk with an increase in stride length as the slope is steeper. It could therefore be hypothesised a more forward tilt of the pelvis in relation to the hip may therefore increase the risk of abutment of the anterior aspect of the femoral head against the acetabulum and therefore causing a greater risk of FAI. While in downhill walking, with greater extension of the hip there is potentially risk of developing Poirier's facets, if they are formed in the way formulated by Odgers et al. (1931). This would also cause the development of cribra as described Angel (1964) and Odgers et al. (1931). Angel (1964) previously suggested the high prevalence rates of Allen's fossa in an ancient Greek sample in comparison to a modern American sample were partly due to differences in terrain. The ancient Greeks lived in a mountainous terrain and therefore they hypothesised the higher prevalence of Allen's fossa is due to hip extension during downhill walking or running. Between males of the two skeletal collections there was no significant difference in the proportions of cribra and therefore it could be associated with terrain being a parallel factor between the two samples. Cribra was not recorded by Lawrence et al. (2018) and the study by Moats et al. (2015) purely focused on alpha angle size. It was therefore not possible to compare this in the same manner as alpha angles, Poirier's facets and plaque. In the current study a link between cribra and alpha angle size was not found for the Wharram Percy sample (when pooled for sex or males only) or the Luís Lopes collection, with no significant difference in mean alpha angle size between those with or without cribra. If terrain is associated with the increase in alpha angle size another mechanism would also need to be involved in the development of cribra.

It is still not clear whether flexion or extension is the lead cause of these traits (Trinkaus, 1975). A study by Acosta et al. (2017) looked at the effect of terrain on entheseal changes of the lower limb. They found individuals from flat terrain had higher entheseal change expression than those from rugged terrain. They believe that those from a more rugged terrain are less likely to have higher expression of entheseal changes as they have higher physiological limits that can respond to the biomechanical loads in comparison to those from flat terrains due to high levels of loading during skeletal development. One area that the males from the rugged terrain showed higher entheseal changes than those from the flat terrain was at the iliopsoas enthesis (Acosta et al., 2017). Angel (1964) proposed the cause of Poirier's facets was associated with the passage of the tendon for the m. iliopsoas during flexion and abduction of the thigh and therefore this could be a possible association in the development of Poirier's facets.

Locomotion patterns due to habitual environment have also been shown to lead to variation in hip morphology. Kappleman (1988) illustrated how the morphology of the bovid femur varies dependent on their habitat. Bovids living in open environments were found to have more rectangular shaped femoral heads. This habitat has little obstacles and the bovids are highly adapted for running. This femoral head shape limits abduction and axial rotation and contributes to hind limb propulsion by preventing unnecessary axial rotation of the limb. While the bovids that lived in the closed environments, such as woodland areas with bushes, shrubs and tree trunks, creating an uneven terrain, had spherical shaped femoral heads. This closed environment limits speed and therefore a hip that is adapted for manoeuvrability. The bovids that lived in broken cover environments showed a more intermediate femoral head morphology (Kappleman, 1988). This habitual adaptation in femoral head shape due to terrain could also be applied to the variation in alpha angle size dependent on terrain. As explained previously, adaptations in posture and muscle function are required in slope walking in comparison to level-ground walking to maintain stability via lowering or raising the bodies' centre-of-mass (Pickle et al., 2016). If a consistent environment, particularly during development, required sloped walking then it is possible there could also be skeletal adaptations. The presence of cam morphology in populations required to mobilise on hillier landscapes (Wharram Percy, Luís Lopes and Kulubnarti) in comparison to predominantly on flatter landscapes (Libben) suggests this could be a contributing factor to its development. Although situated on a hilly landscape Wharram Percy is located on a plateau (Harding and Wrathmell, 2007). It is therefore suggested a combination of terrain and other factors such as physical activity could be involved in the morphological changes in this population. Further work comparing alpha angle size and the non-metric traits of populations of varying terrain is required to understand this possible cause. This would have contributions to bioarchaeological interpretation of non-metric traits of the femur and allow alpha angles to be used as a marker of the habitual environment occupied by past populations.

Table 9-2 Mean alpha angle size comparison from previous studies analysing skeletal collections

Author	Collection	Alpha angle (mean ± S.D.)
Current study	Wharram Percy collection,	Pooled sex: 53.62° ± 11.39° Males: 53.62° ± 11.39° Females: 47.21° ± 11.26°
Current study	Luís Lopes collection, Portugal 19th-20th Century	Males only: 54.18° ± 10.69°
Toogood et al. (2009)	Hamann-Todd collection, Cleveland 20th century	Pooled sex: 45.61° ± 10.46° Males: 47.50° ± 10.71° Females: 43.71° ± 9.88°
Moats et al. (2015)	Libben collection, Ohio	Pooled sex: 35.33° ± 3.87°
Lawrence et al. (2018)	Two cemeteries from Kulubarti site, Nubia (550-800 CE), Mainland & Island	Pooled sites and sex: 41.31° ± 8.53°

Cribra has been associated with development due to its location by the femoral epiphysis and association with younger ages (Smith-Guzman, 2015; Kostick, 1963; Wasterlain et al., 2018; Finnegan, 1978; Stirland, 1996). For both the Luís Lopes and the Wharram Percy samples the frequency of femora with cribra present decreased as age range category increased. The continuous age data for the Luís Lopes collection showed the mean age was significantly higher for femora without cribra compared to those with cribra. Wasterlain et al. (2018) suggested the presence of cribra femoralis could be an indicator of unfavourable conditions during development, including malnutrition, deficiency diseases, non-specific infections and physically demanding work. Both individuals from the Wharram Percy and Luís Lopes populations would have potentially experienced several of these unfavourable conditions. Both populations may have been subjected to times of malnutrition which are likely to have led to deficiency diseases. The Wharram Percy population were likely to suffer from crop failures and there is documentary evidence suggesting food shortages for medieval peasants (Mays, 1995; Gies and Gies, 1990). The soils at Wharram Percy are thin and therefore prone to nutrient exhaustion and it is exposed to harsh climates due to its northerly location and greater elevation, factors increasing the risk of crop failure (Mays, 2007). Harris lines form during periods of arrested bone growth due to childhood illness, and nutritional deficiencies (Mays, 1995). In their study of the Wharram Percy collection, Mays (1995) recorded 37% of juveniles and 23% of adults had Harris lines present. Juveniles with Harris lines present were not short for their ages therefore indicating there were sufficient resources available following the stress period to allow for catch-up growth. This was also confirmed by similar heights in adults with and without Harris lines. However, the thinner cortical measurements for the juveniles with Harris lines present compared to those without suggests there was insufficient resources to catch up on cortical thickness before the child died (Mays, 1995). In must be noted the use of Harris lines as a stress indicator is debated in the literature (Alfonso et al., 2005; Papageorgopoulou et al., 2011; Boucherie et al., 2017). In adults, Mays (1996;1998) observed age-dependant bone loss in Wharram Percy females suggesting a possible cause as poor nutrition in childhood rather than lack of physical activity, as women within these populations were involved in physically demanding work. Examples of cribra orbitalia and rickets were also recorded in the Wharram Percy collection by Mays (2007a), both being associated with nutrient deficiency. With regards to the Luís Lopes collection there were significant socioeconomic changes in Portugal during the 20th century resulting in changes in nutritional status and living conditions. Rapid urbanisation and political instability meant it was not until the 1960s-70s that there was economic and social improvements (Cardoso, 2007). While in Lisbon with rapid population increase, there was an overall decrease per capita of meat consumption by 10% from 1852 to 1925 and 16% between 1906-1925 (Stolz et al., 2013). While cereal and potato production maintained with the population growth (Stolz et al., 2013). Poor living conditions would have led to the spread of infections, illustrated by the cause of death of 15% of individuals from the Luís Lopes collection being tuberculosis (Cardoso, 2006; Matos and Santos, 2006). The price of meat relative to grain declined over the 18th century but then increased into the late 19th century and therefore favouring a diet of less nutritional content required for growth (Stolz et al., 2013). Stature is used to determine the living standards of a population as many environmental factors such as nutritional quality and health have a huge impact on growth (Steckel, 2008; Roberts and Manchester, 2010). A study by Cardoso and Gomes (2008) compared data on stature from various time periods from Mesolithic to Modern day in Portugal. The study found a decrease in stature from middle ages to the late 19th century which they attribute to the change in living conditions in the city centres during this period. They saw a slight increase in stature from the early 20th century, but this then increased dramatically from the late 20th century (Cardoso and Gomes, 2008). This is consistent with the historical and social changes of the time, with at the start of the 20th century Portugal being considered a declining world power and being under a dictatorship until 1974, after which there was improvements in social and economic welfare (Cardoso and Gomes, 2008). Reis (2009) compared the stature information for males between 1840 and 1910 from the centre of Lisbon and those from the countryside. Annually, from 1857, a selection from a list of all Portuguese males of ages 20 and 21, unless exemption was granted on compassionate grounds, were enlisted to the military. It is likely this study only included the poor as exclusion from military service was often granted to the wealth by the local authorities (Reis, 2009). Another problem with this data set is the inability to determine when migration from rural areas to the city occurred, as stature is influenced by the circumstances of childhood. This study found the overall heights of Portuguese military recruits were lower than for other countries during the same period. The urban sample had a slightly higher height than the rural population. This suggests living standards were slightly better in the city compared to the countryside. This difference was however less than half a centimetre and therefore could be due to selection bias or incomplete data (Reis, 2009). These biological indicators of living standards therefore suggest it is possible the cribra recorded on the femur of the Wharram Percy and Luís Lopes collection samples are due to unfavourable conditions, particular nutrient deficiencies, during development as suggested by Wasterlain et al. (2018).

Linked with deficiency diseases, malaria has also been associated with cribra femoralis as discussed in Section 2.3. (Smith-Guzmán, 2015). Malaria was present in Portugal until late 1950s with its elimination in 1973 (Gomes et al., 2016). In addition to this, inferred evidence suggests there was an indigenous malaria in the UK, termed “the ague” (Chin and Welsby, 2004; Reiter, 2000). It has been suggested that malaria was introduced to Britain during the Roman occupation however it did not become endemic until post-medieval period (Gowland and Western, 2012). Smith-Guzmán (2015) suggested femoral cribra should be used in addition to cribra orbitalia and humeral cribra when assessing the skeleton for indicators of malaria. More detail on the cause of cribrous lesions due to malaria can be found in Section 2.3. From the catalogue of burials in ‘Wharrram, A study of Settlement on the Yorkshire Wolds XI, The Churchyard’, it was possible to determine if any individual from the Wharram Percy collection had cribra orbitalia and cribra femoralis present (Mays et al., 2007). Only one individual had both traits present. It is therefore suggested malaria is unlikely to be the cause of the observed cribra femoralis observed in this study. In addition to this, the conditions at Wharram Percy, harsh climate and location, make it in unsuitable environment for mosquitoes, with low land marshy areas suggested as being more suitable (Gowland and Western, 2012; Dobson, 1994). The same information is not available for the Luís Lopes collection sample and therefore further study would be required. In comparison to other factors this is less likely to be the cause of cribra femoralis observed in this study and would require considerable further study.

Femoral head orientation is another important factor to be considered with regards to the association between cam morphology and non-metric traits of the femur with previous studies shown association between alpha angle size and offset ratios (Toogood et al., 2009; Fikkers et al., 2015; Zeng et al., 2016). Significantly negative correlations between offset ratio and alpha angle size for both the Wharram Percy and Luís Lopes collection were found, although moderate to weak. This consistent finding across both samples suggests that as the femoral head becomes more posteriorly translated in relation to the neck it becomes less concave anteriorly. This finding agrees with results from studies by Toogood (2009), Nemtala et al. (2010) and Zeng et al. (2016). Nemtala et al. (2010) found offset ratio to be lower for a group of symptomatic individuals, with an alpha angle >55°, when compared to asymptomatic individuals. While the study by Zeng et al. (2016) showed individuals with osteoarthritis had lower offset ratios and higher alpha angles than those without. From an evolutionary basis, humans showed larger alpha angles and smaller AO/PO in comparison to non-human apes (Fikkers et al., 2015). It was hypothesised that the reduced anterosuperior concavity is an adaptation to resist higher loads of bipedal gait and running, in comparison to in non-human apes. The decreased concavity may increase tensile strength in this region (Fikkers et al., 2015). There was also more variability in alpha angles in humans than non-human apes. The high level of variability in human hips when compared to non-human ape hips suggests this is due to the loading history of this area. Fikkers et al. (2015) suggest the lack of variability in non-human apes shows how important concavity is for climbing apes. Therefore, the lack of concavity in human hips may represent lack of evolutionary advantage. There are two main types of hip morphology; a sturdy hip (coxa recta) or a more mobile hip (coxa rotunda), dependent on the concavity of the femoral head and position of the head in relation to the neck (Hogervorst et al., 2009). At the head-neck junction in a coxa recta hip is a straight section, while the coxa rotunda has continued roundness. With regards to head orientation in relation to the neck, a coxa recta hip has a low offset ratio while a coxa rotunda hip has a high offset ratio, with the hip morphology determining the range of motion in the acetabulum (Hogervorst et al., 2009). Mammals that require a large range of motion have coxa rotunda hips, such as; apes and aquatic mammals. While mammals which do not require such a large range of motion have coxa recta hips e.g. horses (Hogervorst et al., 2009). The coxa recta morphology is better adapted for increased tensile strength while coxa rotunda is better adapted for increased range of impingement free motion (Hogervorst et al., 2009). The higher prevalence of cam morphology in athletes compared to non-athletes seems to contradict this theory as it can be assumed the former would require the greatest range of impingement free motion. This may however be due to the kind of sport being favoured and the requirement for a "stronger" hip which is less exposed to damage. Functional differences of the hip in the development of cam morphology is highlighted by Fraser et al. (2017) by comparing females dance and non-dance athletes. Dancing is extremely demanding on the hip joints due to the required range of motion and requires intense training from a young age (Fraser et al., 2017). The alpha angle size for female dance athletes with FAI was significantly lower than for non-dance athletes with FAI (49.5°± 6.0° vs 53.9° ± 7.3°) (Fraser et al., 2017), which highlights the possible adaptation to a more mobile joint in the dancers. In addition to this, Philippon et al. (2013) reported higher alpha angles and rates of cam morphology in ice hockey players than skiers which they attribute partly to biomechanical cause due to differences in motion at the hip between the two sports. Dickenson et al. (2016a) highlights function adaptation of the hip in the same person. They found in elite golfers the alpha angle size to be significantly lower in the lead hip compared to the trail hip. During the golf swing the lead hip, which is the left hip in right handed players, rapidly goes from external rotation to maximal internal rotation. While the trail hip rotates from internal rotation to external rotation. The authors suggest as the rapid internal rotation is required in the lead hip the reduced alpha angle is advantageous as it allows increased rotation. Therefore, it is possible these loading patterns on the hip prior and during skeletal maturation caused cam morphology to develop and therefore adapting the hip to suit its function (Dickenson et al., 2016). It is possible the adaptation to a femur with less concavity in certain physically activity individuals are to stabilise the joint in response to increased loading, particularly during skeletal maturation which many studies have suggested is the time during which the joint is susceptible to the development of cam morphology (Siebenrock et al., 2011; Siebenrock et al., 2013a; Philippon et al., 2013; Agricola et al, 2014a).

Femoral head orientation in relation to the neck did not have a significant impact on the association between alpha angle size and Poirier's facets, as there was still a significant difference between femora with and without Poirier's facets when controlled for offset ratio for the Wharram Percy collection and Luís Lopes collection. These results suggest the link between Poirier's facets and cam morphology is not impacted by femora head translation. For plaque, when considering the Wharram Percy collection sample, there was not a statistically significant difference in mean alpha angle size between plaque types for both sides when controlled for offset ratio, when prior to controlling for offset ratio there was a significant difference. For the Luís Lopes collection on the right side there was no significant difference in mean alpha angle size between plaque types when controlled for offset ratio but on the left side there was still a significant difference. No study has previously looked at the association between offset ratio and alpha angles on the presence of non-metric traits, therefore these results cannot be compared to determine if they are population dependent. These results suggest only alpha angles impact the presence of Poirier's facets while a combination of femoral head translation (offset ratio) and alpha angles are associated with the presence of plaque. This is likely to be due to Poirier's facets being found in relation to the femoral head only, while plaque can be associated with the femoral head and neck. For plaque types which are mainly focused on the femoral neck (type B & C) to impact concavity, the femoral head would need to be more posteriorly orientated in relation to the neck. Binary regression to determine the accuracy of predicting the presence or absence of cam morphology (based on each threshold value) via data the presence/absence of Poirier's facets and plaque (by type) showed, for the left femora the overall percentage accuracy of predictions was 65.2% at 50° threshold, 66.5% at the 55° threshold and 75.8% at the 60° threshold. The only variables that had a significant impact on predictions were Poirier's facets and type A plaque at each threshold level. For the right side the overall percentage accuracy of predictions were; 65.4%, 73.2% and 79.1% at the 50°, 55° and 60° thresholds. Type A plaque had a significant impact on the predictions at all threshold with the addition of type B at the 55° threshold and Poirier's facets at the 60° threshold. These results further confirm the possible link between Poirier's facets, type A and type B plaque with cam morphology. This regression analysis was limited to males only therefore it is not possible to determine if the same pattern can be observed in females.

These findings contribute to disciplines of bioarchaeology and forensic anthropology in various ways. The link between non-metric traits of the femur (Poirier's facets, plaque type A and type B) with alpha angle size/cam morphology, in both skeletal collections under analysis, further confirms the findings from previous studies e.g. Lawrence et al. (2018). This, therefore, shows these findings are not sample dependent and also begins to build and expand a knowledge base with regards to cam morphology in skeletal collections from varying contextual settings. With the uncertainty surrounding the aetiology and history of both FAI and non-metric traits, increasing the number of studies on various past populations allows the discovery of mutual and conflicting factors. This has the potential to increase knowledge on potential causative factors. Additionally, the link between FAI and non-metric traits allows a wealth of clinical literature focused on FAI to be applied to the bioarchaeological study of these non-metric traits, which is particularly applicable to physical activity.

The link between these non-metric traits with a condition commonly found in athletes adds to the recurrent hypothesis that a leading cause of these traits is increased and strenuous physical activity. This suggests these traits could be used as a marker of habitual activity in past populations (however this will be discussed further in Section 9.2).The exploration of mutual factors between skeletal collections, due to lack of a significant difference in Poirier's facets and alpha angle size between samples, in combination with the literature on previous collections, adds knowledge of additional factors which could lead to the development of these non-metric traits and cam morphology, particularly terrain. It also suggests cam morphology may not entirely be due to physical activity but a functional adaptation to factors leading to instability at the joint. This therefore emphasises the requirement to consider various factors and proceeding with caution when forming interpretations about the sample understudy due to the presence of both non-metric traits and cam morphology. This is also important for the study of bioarchaeology as it highlights the use of cam morphology as a marker of function adaptation due to instability and therefore allows the acquisition of knowledge regarding the lifestyle of the populations under study.

The significant correlation between femoral head orientation and alpha angle size for both collections adds to the discipline of bioarchaeology as this has not be extensively studied. No study has previously looked at this association with regards to the presence of non-metric traits therefore this study adds new data to the discipline. This highlights the need to consider various morphological factors prior to forming interpretations with regards to cause and effect.

Increased awareness of methods of recording cam morphology on bone has contributions to the field of forensics during victim identification, when ante-mortem data of FAI is present. Although the presence of cam morphology cannot be solely relied on for an accurate identification, the ability to record its presence on bone provides an additional identifying feature. Additionally, the link found between cam morphology and Poirier's facets, type A and type B plaque could allow these traits to be used to suggest the presence of cam morphology when the equipment and technology is not present to record alpha angles. The results of this study suggest caution must be taken if attempting to use non-metric traits to infer the presence of cam morphology as there were cases when the alpha angle size was below the diagnostic threshold but some of these traits were present.

9.2. Is there a link between cam morphology & occupation activity?

Cam morphology has typically been associated with athletes. Physically active individuals have been reported to have higher alpha angles and prevalence of cam morphology than non-athletes (Lahner et al., 2014a; Frank et al., 2015; Mascarenhas et al., 2016), as discussed in Section 3.2. In addition to this, those with physically active occupations such as military personnel have also been considered (Coppack et al., 2017; Jochimsen et al., 2019). If athletic activity is an influential factor it is hypothesised that occupational activity could also impact the development of cam morphology, which has not previously been investigated. If physically demanding occupations and lifestyles have an impact on the presence of cam morphology it is hypothesised that those from rural populations are more likely to have cam morphology than urban populations. In addition to this further commonly used methods used bioarchaeologically to determine differing activity levels will also be discussed such as; sexual division of labour and side asymmetry.

Occupational physical activity differences

For the Luís Lopes collection sample, there was no significant difference in alpha angle size between ISCO-08 occupation categories. Although this difference was not significant the elementary occupations group had the highest mean alpha angle size for both sides. This occupational category included gravediggers and factory workers which were likely to have been engaged in physically demanding tasks as part of their occupations. For both sides, if the undetermined category is excluded, clerical support workers had the lowest mean alpha angle size. This category includes occupations such as; office employees and clerks who are less likely to have been engaged in physically demanding tasks as part of their day to day work. When considering the left and right side separately, for the left side, after elementary occupations, the next highest mean alpha angle was for the armed forces occupations. Due to the physically demanding aspect of military training they are an at-risk population for the development of FAI (Coppack et al., 2017). Military personnel over 40 years of age are more likely to develop osteoarthritis due to FAI than the general population according to the study by Jochimsen et al. (2019). They suggest this is due to the forces placed on the hip during military training being above those normally subjected to this area. Differences in prevalence rates of osteoarthritis have also been recorded between the services and ranks (Scher et al., 2009). With FAI being considered a leading cause of osteoarthritis of the hip in active populations there is a possibility these high rates of osteoarthritis in military could be, in part, associated to high rates of FAI/cam morphology. The high alpha angle size found in the armed forces occupations from the current study agrees with the literature by Ochoa et al. (2010) which reported at least one finding of FAI in 87% of a young military population. Jochimsen and colleagues however did not find a statistically significant difference in mean alpha angle size between military veterans and civilian patients with end-stage hip osteoarthritis, (64.3°±13.2° vs 61.1°± 11.5°, respectively) or the prevalence of cam deformity, based on an alpha angle threshold of ≥60° (Jochimsen et al., 2019). This study was limited due to lack of information on activity level, military branch and number of years in service, which Scher et al. (2009) has previously reported to impact the level of osteoarthritis. In addition to this, the civilian patients all suffered from FAI and therefore are likely to have high rates of either cam or pincer morphology. For the right side the next highest mean alpha angle size was for services and sales workers. This category included occupations such as; shop assistants, guards and doormen. These occupations were likely to have spent a lot of time stood up. The task activity from the compendium of physical activity included predominantly ‘standing tasks, light effort’ and therefore a large amount of weight bearing on this joint.

When occupational data was categorised by physical activity levels using MET values overall there was no significant correlation found between alpha angles and MET values for the left or right side. For method I, alpha angle size increased from low activity group to moderate activity group to high activity group for the right side, while for the left side the mean alpha angle size decreased from low activity to moderate activity but it was still highest for high activity. This difference was, however, not found to be statistically significant on either side. For method II, for both left and right side mean alpha angle size increased from the sedentary behaviour group to light intensity to moderate intensity group. This difference again was not statistically significant. These results could indicate a limited association between occupational activity and cam morphology but it also could be due to the method used to categorise occupational physical activity. Winburn (2019) and Winburn and Stock (2019) are currently the only other studies to use MET values to categorise physical activity within the bioarchaeological literature. In their study, Winburn (2019) did not find a correlation between activity, as assessed by MET values, and acetabular degeneration, while Winburn and Stock (2019) showed MET values were significant predicators of osteoarthritis in the hand only (Winburn and Stock, 2019). It is therefore not clear how well this method reflects activity rates of past populations. The compendium was designed to be used with standardised recordings of daily activities from self-reported questionnaires. This study did not have this information available and although occupational activities from the ISCO-08 were used, this does not give an accurate representation of the exact tasks carried out per occupation. These results are also limited as MET values provide an estimated metabolic rate for certain activities. This does not equate to a value of the biomechanical strain on the joint for each occupation e.g. greater loading on the lower body or upper body. Method III did not use MET values, but instead, occupations were categorised as manual or non-manual via a database compiled from categorised occupations from previous studies using identified skeletal collections (Perréard Lopreno et al., 2012). For both left and right side, this method also did not show a significant difference between occupations categorised as manual and non-manual. This highlights the use of MET values is not the only cause for the lack of significant difference in alpha angle size between the occupations groups however it still does not address the biomechanical limitations. Overall there were patterns in alpha angle size between occupations of varying physical activity however this was not found to be significantly different for any of the methods used. This indicated alpha angle size does not seem to be affected by occupational physical activity in adults when categorised using the methods from this study. This could be due to occupation data only representing the habitual physical activity as adults. Various studies have previously suggested cam morphology develops during skeletal immaturity (as discussed in section 3.2) and therefore occupational information from adults may not be an influencing factor in the development of FAI.

If cam morphology is associated with a more physically demanding lifestyle then femora from the Wharram Percy sample, an agricultural population, should have significantly higher mean alpha angles than the Luís Lopes collection, a late 19th to early 20th century urban population. It is likely the agricultural lifestyle for the individuals from the Wharram Percy population was highly strenuous suggested by historical record and studies of skeletal changes (Bennett, 1987; Judd and Roberts, 1999; Sofaer Derevenski, 2000; Mays et al., 1999). In this study, there was however no significant difference in mean alpha angle size between these two populations on either side when comparing males only (no females were included in this study from the Lisbon sample). Considering some occupations within an urban setting may also be physically demanding, when comparisons between activity categories within the Luís Lopes collection and with the Wharram Percy sample were made this again showed no significant differences in mean alpha angle size. Further to this, the mean alpha angle size for the Wharram Percy sample was not the highest, as would have been expected if physical activity had an impact of the presence of cam morphology. In their analysis of the Luís Lopes and Sassari identified collection, Calce et al. (2018) reported increased femoral robusticity significantly correlated with lower pelvic osteoarthritis score. They suggested it is possible these adults may have been active as children which produced the more robust bones measured in adulthood. The historical record shows in the late 19th and early 20th century there was a high level of movement from agricultural settlements into the cities in Portugal. Calce et al. (2018) therefore suggests if these individuals were engaged in physically demanding activities, which are associated with lifestyle in farming settlements, during childhood this could be the cause of the femoral robusticity reported in their study. If cam morphology is a developmental phenomenon, as described by Siebenrock et al. (2011) and Agricola et al. (2014a), these findings by Calce et al. (2018) may explain why there is not a significant difference in alpha angle size by occupational physical activity in adulthood and the lack of significant difference with the Wharram Percy collection sample mean alpha angle. In addition to this, although migration to Lisbon was increasing, no more than 6.9% migrated before the age of 10 years old and therefore spent the period of skeletal maturation in agricultural settings (Rodrigues, 1994 as cited by Reis, 2009). Children were also commonly involved in manual labour before the age of 12 years of age, with some industries’ work force being made up of 25% children in Lisbon. It was not until after the 1950s and 60s that child labour laws became stricter and prevented this kind of work (Cardoso and Garcia, 2009).

These factors suggest both the Luís Lopes and Wharram Percy sample may have been subject to high levels of physical activity during childhood and therefore obscure the results of occupational physical activity in adulthood. Furthermore, from the findings in the previous section of this discussion, additional extrinsic factors requiring adaption to provide additional stability to the joint may have also played an important role. It must also be noted that the Wharram Percy sample was not limited to one chronological phase and therefore represents approximately 900 years. It cannot be assumed that the level of habitual activity was consistent across this time period with the advent of new technologies and practices. This could also be a contributing factor to the lack of significant difference between the two collection.

The apparent lack of association between cam morphology, and occupational physical activity shown in this study contributes to the field of bioarchaeology by advising that this condition should not be used as a marker of activity in adults. Instead the findings and discussion indicate it would be more useful as an indicator of activity prior to and during maturation. Although cam morphology occurs more frequently in athletes than non-athletes (as shown in Section 3.2. and 3.3.) caution must be taken when interpreting its presence in relation to activity of past populations. The results of this study suggests, as previously suggested by Agricola et al. (2014a) and Gala et al. (2016), that cam morphology and alpha angle size remains consistent in adults. Therefore, the use of this condition as a marker of activity during development would be extremely useful in the study of past populations to determine more about the lifestyles of juveniles, as it remains present in adults. Additionally, this is one of few studies, within the fields of bioarchaeology and forensic anthropology which uses MET values to categorise physical activity. Further awareness and use of this method would be of values to the disciplines of forensic anthropology and bioarchaeology in the study of markers of activity, to reduce subjectivity imposed by the researcher through the use of predefined values for each activity and allow the creation of comparable data between studies.

Difference in alpha angles between males and females - sexual division of labour or sexual dimorphism?

Lawrence et al. (2018) suggested the differences in alpha angle size between males and females in their study of the Early Christian site of Kulubnarti, Nubia, is due to the sexual division of labour, with men being involved in more physically demanding activities than females. For the Wharram Percy collection the mean alpha angle sizes, for both left and right sides, were statistically significantly higher for males compared to females. There was also a higher prevalence of males with cam morphology at each alpha angle threshold than females. This difference between males and females is in agreement with the literature, with cam morphology being reported more commonly in men than women, at a 14:1 ratio (De Bruin et al., 2013). When comparing male and female athletes several studies have shown there is typically a higher mean alpha angle size for males when compared to females. For instance, in their study of male and female professional soccer players Gerhardt et al. (2012) found the overall mean alpha angle size for males was 65.6° while it was 52.9° for the females. The females, however, had on average, less years of playing professional soccer than the males, which maybe a contributing factor. Johnson et al. (2012) also reported a difference in the mean alpha angle size between male and female who competed in semi-professional or high-level recreational soccer during skeletal immaturity. In males, the mean alpha angle size for the right side was 57.5° and 55.1° for the left side. While for females the mean alpha angle size was 50.0° for the right side and 49.2° for the left side. The lower mean alpha angle size reported in female athletes when compared to male athletes suggests this difference observed in the Wharram Percy collection is not likely to be indicative of differences in physically demanding activities between the sexes but more likely another of the aetiological factors. The alpha angle size for the FAI and non-FAI group did not consistently show a higher alpha angle size for males compared to females. This difference in alpha angle size between males and females could be due to the low sample size with only five females and seven males in the non-FAI group and twelves males but only six females in the FAI group. Additionally, occupation and recreational activity information was not available for this sample therefore it cannot be determined if there was a significant difference in physical activity between these individuals.

It is currently unclear as to why a difference in alpha angle size between males and females exists with various hypotheses being advocated such as; differing levels of physical activity during the times of epiphyseal closure between the sexes (Levy et al., 2015), anatomical differences (Hogervorst et al., 2009; Hogervorst et al., 2011), inappropriate cut-off values (Nepple et al., 2014) and also fewer studies including female athletes (Levy et al., 2015). It is nevertheless challenging to determine the true difference between males and females due to the range of alpha angle thresholds used to determine the presence of cam morphology, differing imaging modalities and imaging view selected between studies. Table 9-3 shows the rates of cam morphology and differences in alpha angles between males and females from various studies.

It is difficult to establish if the differing levels of physical activity during the time of epiphyseal fusion is the true cause as, although several studies have identified an association between cam morphology and athletic activity at the time of skeletal maturation, many of these studies focus solely on males (Siebenrock et al., 2011; Siebenrock et al., 2013; Philippon et al., 2013; Agricola et al., 2012). In medieval rural populations males, females and children were involved in physically demanding work (Mays, 2007a). Children began work as young as five years of age and, although both sexes were engaged in strenuous physical labour, there was still an element of sexual distinction in certain tasks (Bennett, 1987). This difference in tasks between girls and boys in this population during skeletal maturation may be the cause of these differences in alpha angle size between the sexes. Fraser et al. (2017) exclusively focused on the effect of athletic activity during maturation in females only. In this study, they compared young female dance athletes to young female athletes involved in sports such as soccer, running or ice hockey, both groups having a diagnosis of FAI. Using a cut off value of >55°, 18.3% of the hips of dance athletes and 42.5% of the hips of non-dance had cam morphology (Fraser et al., 2017). The high rates of cam morphology in young female non-dance athletes are similar to the young male athletes reported in previous studies. This therefore suggests sexual division in tasks performed during skeletal maturation could be the cause of these differences in alpha angle size. On the other hand, in their study of cam morphology development in pre- and post-epiphyseal closure in non-athletes Carsen et al. (2014) showed cam morphology (based on an alpha angle ≥ 50° threshold) to only be present in boys and not girls with closed epiphysis. In addition to this the boys had a significantly higher mean alpha angle than girls (43.4° ± 6.0 vs 37.8° ± 4.0). This difference in alpha angle size in non-athletic individuals suggests this may also be due to morphological differences between males and females. This could also be due to the difference in rates of non-metric traits present between males and females, as discussed in 9.1.

With regards to human hip morphology, although debated, typically females are more likely to have coxa profunda; a deep acetabulum, a round femoral head with normal or high head-neck offset (coxa rotunda femoral head). Males are more likely to have coxa recta; aspherical femoral head with asymmetrical head-neck offset on a thick and short femoral neck (Hogervorst et al., 2009). Hogervost et al. (2011) theorised from an evolutionary standpoint this variation is largely due to the obstetric requirements in females. The true pelvis is widened, which places the acetabulae further apart. To compensate for this the acetabulum tends to be deeper to preserve balance of the mechanical stresses from body weight on this area and reducing the abductor force to maintain a level pelvis during normal gait. The common hip morphology to adapt to this is coxa profunda (Hogervorst et al., 2009). For males, the hip is not adapted for childbirth and therefore loading plays a larger role in the morphology to allow for a more stable joint for bipedal gait therefore coxa recta morphology is more common (Hogervorst et al., 2009).

Studies by Levy et al. (2015) and Nepple et al. (2014) have shown alpha angle size in females with FAI are typically lower than in males with FAI. In their study of females with symptomatic non-arthritic intra-articular hip pain Levy et al. (2015) reported only 29.7% of symptomatic females had an alpha angle >50.5° (Levy et al., 2015). In a sample of males and female patients with FAI, Nepple et al. (2014) showed mean alpha angle size was significantly higher for males than females, with a mean maximum alpha angle size of 57.6° in females and 70.8° in males. In addition to this, 34% of females compared to 72% of males had a maximum alpha angle >60° (Nepple et al., 2014). When Hooper et al. (2016) compared hip morphology of adolescent males to adolescent females undergoing hip arthroscopy for FAI the mean alpha angle for males was 53.1° and 42.5° for females, with 38.9% of males and only 1% of females considered to have cam morphology (using an alpha angle cut-off of 55°). These studies suggest symptoms are present in females at a lower alpha angle size than in males. This is also highlighted by the use sex dependent pathological thresholds have been developed with lower alpha angle thresholds for females (Gosvig et al., 2007). The deeper acetabulae in females would cause impingement at smaller alpha angles than in males, with their shallower acetabulae, and this maybe the contributing factors to the lower alpha angle size in females in the current study and previous studies rather than the sexual division of labour.

The alpha angle size of the females in the Wharram Percy collection are more in line with those of modern athletes. This could be indicative of the physically demanding lifestyle of the Wharram Percy females from a young age which agrees with the findings by Mays, (2007a) which suggested the high levels of osteoarthritis on the femur in females from this collection was due to physically demanding work placing mechanical stress on the lower limb. It is likely that the difference in alpha angle size and prevalence of cam morphology between males and females is less to do with the sexual division of labour in adults but more likely to be due to morphological differences and possibly sexual distinction of tasks during childhood. These findings add to the current knowledge of this condition in skeletal collections, particularly in bioarchaeological study, which has previously interpreted these differences between sexes as solely due to difference in the level of physicality in habitual activities, e.g. Lawrence et al. (2018). The use of alpha angles to determine level of physical activity during childhood would be extremely useful for the study of past populations. It also highlights the importance of incorporating sex dependent alpha angle thresholds in future studies due to the morphological differences between males and females at this area. This will give a better representation of the prevalence rates of cam morphology in females compared to males.

Table 9-3 alpha angle size and the prevalence of cam morphology in studies including males and females

Author	Sample	Imaging modality and view alpha angles measured on	Cam morphology alpha angle threshold	Mean alpha angle & prevalence of cam
Hooper et al. (2016)	177 adolescents • Having hip arthroscopy • Hip pain & signs and symptoms of chondrolabral hip damage • Age: 13-18 years • 129 females • 48 males	Frog-leg lateral or 45° Dunn lateral hip radiographs Axial oblique plane on hip MRI scans	55° on MRI	Unadjusted alpha angles Plain radiographs: Males 56.3° Females 45.1° Axial oblique MRI: Males 53.1° Females 42.5° Cam morphology: Males 38.9% Females 1%

Allen et al. (2009)	113 patients with symptomatic cam morphology • 82 males • 31 females • mean age 37.9 years • age range 16-55 years	Cross-table lateral radiographs or Dunn view	55.5°	Males 69.1°±10.4 Females 62.1°±9.6
Levy et al. (2015)	391 female patients with non-arthritic symptomatic intra-articular hip pain • mean age 36.1 ± 12.3 years	AP-pelvis and lateral radiographs Frog-leg lateral Cross-table lateral 90° Dunn lateral (largest alpha angle used)	Pathological >57° Borderline 51-56° Normal ≤42°	Overall mean on frog-leg lateral: 48.2° ± 11.9 AP: 41.3° ± 12.2 Cross table lateral: 43.7° ± 10.3 90° Dunn lateral: 44.2°± 8.6 Pathological 14.6% Borderline 15.1% Normal 35.6%
Nepple et al. (2014)	55 male and 55 female patients • with FAI & undergoing surgical treatment	Frog-leg lateral, Dunn lateral & AP	Multiple thresholds	Mean alpha angle on AP: males 64.9° Females 49.0° Dunn: Males 65.3° Females 53.1° Frog-leg: Males 56.9° Females 45.7° <50° males 6% females 30%
Gosvig et al. (2007)	2803 individuals from Copenhagen Osteoarthritis Study • 1055 males • 1749 females 164 patients for total hip replacement • 82 males • 82 females	AP and lateral radiographs	Normal: Males ≤69° Females ≤50° Borderline Males 69° to 82° Females 51° to 56° Pathological Males ≥83° Females ≥57°	Copenhagen Osteoarthritis Study individuals (AP): Males right side 51.7°±13.5 Males left side 53.1°±13.9 Females right side 44.4°±5.5 Females left side 45.5°±5.1 Total hip replacement patient: Males (AP): 71° Males (lateral): 61° Females (AP): 59° Females (lateral):59° Males Normal 40% Borderline 16% Pathological 44% Females

				Normal 59% Borderline 6% Pathological 35%
Pollard et al. (2010a)	83 from asymptomatic individuals 44 females 39 males	cross-table lateral radiographs	-	Males: 48° ± 8 Females: 47° ± 8

Directional asymmetry of cam morphology

Functional interpretations have been made by observing differing levels of side asymmetry of various skeletal changes. Right sided dominance of the upper limb is observed more commonly than left in most human populations (Larsen, 2015b). For the lower limb, side dominance is not as clearly expressed as in the upper limb due to weight bearing typically being evenly distributed during normal gait (Auerbach and Ruff, 2006). Unlike the upper limb, the dominant lower limb typically show less robusticity than the non-dominant limb (termed crossed symmetry) as the non-dominant side provides postural stabilisation (Auerbach and Ruff, 2006). There is typically a higher frequency of right-footedness as with handedness (Peters and Durding, 1979; Gentry and Gabbard, 1995) but studies have suggested the left leg is used for weight-bearing regardless of handedness (Macho, 1991). For each of the samples the left femora consistently had a higher alpha angle than the right, this was however only statistically significant in the Wharram Percy collection. It has also been suggested that directional asymmetry is higher in individuals subjected to higher levels of stress (Kujanová et al., 2008) therefore this may be indicative of the more physically demanding lifestyles of this agricultural population in comparison to a modern British population and a urban late 19th-early 20th century Portuguese population. When analysing side asymmetry within the occupation categories there was only a significant difference in mean alpha angle size between left and right sides for the armed forces occupations, with the mean alpha angle size being significantly higher for the left side than the right side. In addition to this, for both the Wharram Percy (when pooled for sex and separated into males and females only) and Luís Lopes collection samples, there was no significant difference in the proportions of femora with cam morphology between the left and right side based on any of the thresholds used in this study (≥50°, ≥55° or ≥60°).

There are few studies which report directional asymmetry for cam morphology and alpha angle size. One of the few studies, on side differences and limb dominance with FAI, by Mascarenhas et al. (2018) found no significant difference in alpha angle size between sides, and limb dominance did not have an impact. This was however a study of asymptomatic individuals with no information of activity levels. Tak et al. (2015) also did not find cam morphology to be more prevalent on the dominant leg in comparison to the non-dominant leg in their study of professional elite football players. While in their study Dickenson et al. (2016a) suggest increased alpha angles at one hip over the other is potentially an adaptation to suit the common function. When analysing hip morphology elite golfers, they found alpha angles to be significantly lower in the lead hip compared to the trail hip. Cam morphology, as determined by alpha angle >55°, was present in 16% of players, with the trail hip only being affected in seven and bilateral cam morphology occurring in two players (Dickenson et al., 2016a). In the Wharram Percy collection and the armed forces occupations of the Luís Lopes collection, the side asymmetry, with higher alpha angles on the left side, typically the stabilising hip, may be due to high-levels of loading activities. When comparing alpha angle size for the kicking leg of professional to amateur soccer players Lahner et al. (2014b) found a significantly higher alpha angle size for the kicking leg of professional soccer players (57.3° ± 8.2°) than in amateur soccer players (51.7° ± 4.8°). This would contradict this finding as it suggests the hip with greater movement (the kicking leg) has the higher alpha angle size as opposed to the stabilising side. There are also mixed findings when comparing alpha angle size for the left and right side in both athletes and non-athletes as shown in Table 9-4 below.

It is therefore possible that the significantly higher alpha angle size on the left femora for the Wharram Percy collection males and the Luís Lopes collection, armed force occupations, could be indicative of functional adaptation during skeletal maturation. For the samples in this study the left femora consistently displayed higher mean alpha angles. It could be theorised this is due to this side typically being the stabilising leg and subject to a great amount of weight bearing. The lack of a significant difference in the prevalence of cam morphology at any threshold for either collection however suggests side asymmetry is not an influencing factor when considering alpha angles. It is not clear however if the concept of crossed symmetry applies to alpha angle size.

Table 9-4 Alpha angle size on left and right side, for the current study and the literature of athletes and non-athletes

Study	Sample	Mean alpha angle	
		Left	Right
Current	Wharram Percy (pooled sex)	53.0° ± 12.2°	50.1° ± 10.5°
	Wharram Percy (males)	55.1° ± 12.3°	52.0° ± 10.4°
	Wharram Percy (females)	48.4° ± 11.2°	45.8° ± 10.0°
	Luís Lopes (males)	54.6° ± 10.9°	53.7° ± 11.3°
	FAI group (pooled sex)	54.6° ± 9.9°	52.6° ± 7.6°
	Non-FAI group (pooled sex)	52.5° ± 8.6°	49.79 ± 7.4°
Farrell et al. (2016)	Elite rugby union players	52.3° ± 11.7°	49.5°± 12.2°
Gosvig et al. (2007)	Non-athlete male	53.1° ± 13.9°	51.7° ± 13.5°
	Non-athlete female	45.5° ± 5.1°	44.4° ± 5.5°
Lahner et al. (2014a)	Elite track and field athletes	50.1° ± 5.57°	(54.4° ± 8.25°
	Non-athletic controls	47.6° ± 3.5°	48.6° ± 6.94°
Lahner et al. (2014b)	Semi-professional soccer players	55.4° ± 6.52°	57.0° ± 8.32°
	Amateur soccer players	52.2° ± 4.8°	51.8° ± 4.8°

9.3. Are there any osseous differences between those investigated for FAI and those without FAI?

The 3D volume rendered CT models of individuals being investigated for FAI (FAI group) and a random sample of controls (non-FAI group) permitted the investigation of observable osseous differences between those with clinical symptoms of FAI and those without. A diagnosis of FAI requires symptoms, positive clinical signs and imaging findings (Griffin et al., 2016). It is therefore currently not possible to determine the presence of FAI on skeletal remains without a clinical history. Although cam morphology is a leading cause of FAI and can be observed on bone, several studies have reported prevalence rates in asymptomatic populations and therefore it cannot be used as an indicator for symptoms (Reichenbach et al., 2010; Hack et al., 2010; Jung et al., 2011; De Bruin et al., 2013). The identification of any further osseous changes in those with symptoms compared to those without would allow the identification of this condition on bone, when it is not possible to access clinical information e.g. in the analysis of archaeological populations.

Increased alpha angle size has been reported to be an indicator of those with symptomatic cam morphology (Khanna et al., 2014; Allen et al., 2009; Barrientos et al., 2016; Larson et al., 2013). The overall mean alpha angle size in the current study was higher for the FAI group compared to the non-FAI group, 53.57° vs 51.06°, however, for both sides this was not significant. This suggests alpha angle size is not indicative of symptoms. In their study Sutter et al. (2012) found considerable overlap in alpha angle size between patients with FAI and asymptomatic volunteers, suggesting alpha angles are not accurate enough to discriminate between symptomatic and asymptomatic individuals. While Hack et al. (2010) found 14% of asymptomatic volunteers had cam morphology (based on a threshold value of >50.5°) on at least one hip. In the current study, it was unknown which hip was under investigation for FAI and therefore symptomatic. If the symptomatic hip was compared to non-FAI group this may have shown a significant difference. In addition to this, due to the retrospective nature of these images it was unknown if the non-FAI group ever have or currently suffer from FAI symptoms. Further study is therefore required with information on symptoms side, a control group without a history of FAI symptoms and larger sample sizes, to determine if larger alpha angle sizes is a good indicator of FAI due to cam morphology.

With regards to non-metric traits at the anterior aspect of the femur between the FAI and non-FAI group, there was no significant differences in the proportions of femora with or without Poirier's facets present. There was however a higher prevalence of femora with Poirier's facets present for the FAI group (right: 38.9%, left: 33.3%) compared to the non-FAI group (right: 16.7%, left: 16.7%) for both sides. The higher rates of recorded Poirier's facets in individuals being investigated for FAI, could indicate the presence of Poirier's facts being associated with the development of symptomatic cam morphology/FAI, this difference was however not significant. There was also no significant difference in the proportions of femora with or without plaque (and by types) between the FAI and non-FAI groups, suggesting plaque is also not a useful indication of symptomatic hips. There are currently no previous studies using clinical images to determine if there is a difference in the prevalence of non-metric traits between individuals being investigated for FAI and controls. It is therefore not possible to compare the findings in the current study to other population groups. These findings however suggest neither Poirier's facets or plaque can be used to distinguish cam morphology in symptomatic individuals from asymptomatic individuals. Due to the reasons mentioned previously this cannot be definitively stated without further study.

During the analysis of both the CT models and the skeletal collections circular eroded areas were noted. For the skeletal collections these areas were not classified as cribra according to Radi et al. (2013)'s recording criteria as their location and appearance did not fit with the descriptions and image references provided in their article. Instead, these areas appeared to represent herniation pits as described by Pitt and colleagues in 1982 as; *"round to oval radiolucency surrounded by a thin zone of sclerosis…identified in the proximal superior quadrant of the adult femoral necks"* (Pitt et al., 1982). Using MR images of the dancers in split position Kolo et al. (2013) noted the herniation pits were located at the contact zone between the anterosuperior femoral head-neck junction and the acetabulum, and therefore are potentially due to repeated abutment of the femoral head against the acetabular rim. Herniation pits have also been suggested to be markers of FAI caused by cam morphology (Panzer et al., 2010). Villotte and Knüsel (2009) suggested herniation pits could be associated with Allen's fossa however it is difficult to determine if this is the case as the original description of herniation pits were made on radiographs while the cervical fossa of Allen was originally described through observations on dry bone specimens.

In this study, osseous pits believed to be herniation pits were identified on three femora from the FAI group and four femora from the non-FAI group. While for the skeletal samples, for the Luís Lopes collection they were noted on six femora and for the Wharram Percy collection they were seen on nineteen femora. Many authors have reported an association between herniation pits and higher alpha angle size (Panzer et al., 2008; Kavanagh et al., 2011; Guo et al., 2013; Laborie et al. 2011). Panzer et al. (2008) found alpha angles were significantly higher in those with herniation pits compared to those without, 55.2°± 11.9 and 49.8° ± 9.3 respectively. Kavanagh et al. (2011) also found an association between hips with cam morphology and herniation pits using surface 3D reconstructions from MRI arthographic images. They found 7 of 42 patients had herniation pits but like Panzer et al. (2008) there was an association with cam morphology. Using CT imaging Guo et al. (2013) also found alpha angle size to be larger in those with herniation pits than those without. A limitation to this study can be seen in their exclusion criteria where any individual with a bony bump at the femoral head neck junction was excluded. They were therefore excluding individuals likely to have FAI from this study. Unfortunately, these studies did not provide information on clinical presentation for the cases included therefore it was not possible to determine if the herniation pits and increased alpha angle size were associated with symptoms.

For the Wharram Percy collection there was no significant difference in mean alpha angle size between femora with and without herniation pits on either side. For the Luís Lopes collection there was only two femora on the right side therefore statistical analysis was not possible, however, for the left side there was no significant difference in alpha angle size between femora with and without herniation pits. While for the clinical CT samples, when considering the FAI group only it was not possible to run statistics on either side due to the small number of femora with herniation pits present. For the non-FAI group, on the right side, there was no significant difference while for the left side no femora had herniation pits present. When considering the clinical CT samples together, on the right side there was a significant difference, with femora with herniation pits present having a significantly higher alpha angle size than those without herniation pits. Unlike the current literature, the data from both skeletal collections suggest the herniation pits are not associated with alpha angle size and therefore cam morphology. This agrees with results from the study by Ji et al. (2014) that showed no association between alpha angle size and herniation pits however they were significantly associated with pincer morphology in symptomatic patients. There was also a significantly higher prevalence of herniation pits in symptomatic individuals in comparison to asymptomatic individuals. The non-FAI group in the current study showed a higher prevalence of herniation pits (20%) compared to the FAI group (9.1%) therefore, it is suggested this feature cannot be used to indicate symptoms.

The ability to identify osseous changes present for symptomatic individuals but not asymptomatic individuals has applications for bioarchaeology and forensic anthropology. From a bioarchaeological standpoint enabling the identification of FAI when a clinical history is not present is important as this information is often not present for archaeological populations. Additionally, due to the activity limiting nature of FAI identification symptomatic individuals from asymptomatic would be extreme beneficial. Pain and functional limitations are the most common symptom of FAI, with many individuals reporting problems carrying out activities of daily living (Philippon et al., 2007). In populations where substance strategies are dependent on the ability to engage in physically demanding activities, knowledge of how to identify a condition on bone which could limit these actions would be of great interest in interpreting lifestyles of past populations. Additionally, the ability to separate those who are symptomatic from those who are asymptomatic in past populations would allow further interpretations about the natural history of this condition to be made.

From a forensic perspective, as discussed previously, the capability to identify any condition on bone which match ante-mortem data would be of great value in victim identification. Unfortunately, the results of this study suggest there are no osseous changes that are indicative of symptomatic individuals with FAI due to cam morphology. The higher prevalence of Poirier's facets in the FAI group compared to the non-FAI group suggests this non-metric trait could be indicative of a form of cam morphology which is more likely to become symptomatic however this difference was no significant. The lack of significant osseous changes which are indicative of FAI in this study could be due to the low number of individuals with these traits present, therefore limited statistical analysis could be included. Further study with larger sample sizes are therefore required to confirm the current findings. Additionally, due to the retrospective nature of the images for both the FAI and non-FAI groups, interpretation of these findings was limited. Future studies with knowledge of the side with symptoms present for the FAI group, as well as the occupational and recreational activities, for both groups would address some of these limitations.

9.4. Is there a link between cam morphology & osteitis pubis?

Various studies have suggested an association between cam morphology and osteitis pubis (Phillips et al., 2016; Hammoud et al., 2014; Matsuda et al., 2015). Age at death interpretation is an essential part of both bioarchaeological and forensic skeletal analysis. Osteitis pubis, or pubic symphysis stress injury, causes both soft tissue lesions and bony alterations which resemble the later phases of degenerative changes described in age estimation methods focused at the pubic symphysis (Mays, 2015). This may therefore cause degenerative changes at the pubic symphysis at an early age in "at risk" individuals, such as athletes. Using the recording criteria developed in this study (porosity, erosions, irregularity and osteophytes) there was no significant difference in alpha angle size between individuals with and without each of these traits present with the exception of erosions (on both symphysial sides and femoral sides) and irregularity (on the left pubic symphyses and alpha angle size on the left femora). Eburnation was excluded from analysis due to the small number of pubic symphysis with this trait present. For the Luís Lopes collection, after adjusting for age there was no significant difference in mean alpha angle size for individuals with and without each trait. When controlled for age neither erosions or irregularities showed a significant difference in alpha angle size. This was however limited due to the test assumptions not being met for these traits on certain sides. The results of this study therefore suggest alpha angle size does not have an impact on the presence of traits associated with osteitis pubis.

Judd (2010) described a possible case of osteitis pubis on the pubic symphysis of an individual from Hierakonpolis (Egypt) dated to 2080-1700 BC. The pubic symphysis showed excessive flattening and polishing of the face. These changes are attributed to osteitis pubis due to physical activity (Judd, 2010). The fragmentary nature of the remains however made interpretation difficult. For the Luís Lopes collection there were two cases where the pubic symphysis was extremely flat with no distinct features. These two cases may be examples similar to that observed by Judd (2010). In addition to this, when analysing the three cases reported to have eburnation present, all had at least one hip with an alpha angle size >55°. Eburnation was a common feature recorded in the archaeological case reports of possible osteitis pubis by Pfeiffer, (2011) and Judd (2010). Eburnation is one of the commonly used features to determine the presence of osteoarthritis on skeletal remains and typically reflects the later stages of this condition (Waldron, 2019). In addition to this, Calce et al. (2017) referred to osteitis pubis when scoring osteoarthritis on the skeleton. The pubic symphysis is capable of a small amount of movement (Becker et al., 2010) therefore osteitis pubis may be a reaction to, or a form of osteoarthritis at this joint. This theory is supported by Phillips et al. (2016) who suggests the decreased range of motion from FAI causes repetitive loading of the pubic symphysis leading to hypermobility of the pubic symphysis resulting in osteitis pubis. The osseous changes to the pubic symphysis caused by osteitis pubis may therefore only be distinguishable from age related changes at the later stage of this condition.

Further work needs to be carried out on osteitis pubis. Several studies have suggested possible recordings of this condition on skeletal remains (Gregg and Bass, 1996; Judd, 2010; Pfeiffer, 2011) however this is the first study to attempt to form set recording criteria. Additional work with the use of medical images of individuals with osteitis pubis would be invaluable and allow refinement of the recording criteria. The inter and intra-observer error rates for the osteitis pubis criteria ranged from poor to good, likely due to lack of familiarity and training, and lack of images provided with the recording criteria. The inclusion of entheseal attachment site changes may also improve the criteria. Several studies have reported changes at these sites associated with osteitis pubis (Andrews and Carek, 1998; Beatty, 2012; Cunningham et al., 2007; Desmond et al., 1994). Furthermore, several radiographic signs used to diagnose osteitis pubis in the living cannot be observed on bone e.g. pubic symphyseal widening and instability as well as bone marrow oedema. Therefore, it may not be possible to record the early stages of osteitis pubis on bone.

Although the poor error rate results make it difficult to draw any clear conclusions with regards to the presence of osteitis pubis and cam morphology, this study still contributes knowledge to the disciplines of bioarchaeology and forensic anthropology through raising awareness of this under-studied condition. Currently, as discussed in chapter 3.4, osteitis pubis is only addressed in the biological anthropology literature as case studies. No research has attempted to form recording criteria to assist in the identification of this condition on bone. Mays (2015) addresses osteitis pubis as a potential impacting factor on the accuracy of age estimations using methods focused at the pubic symphysis however this condition has not been studied further. Several of the osseous changes used clinically to diagnose osteitis pubis radiologically are similar to end stage traits in various age estimation methods, therefore this condition could lead to an over estimation of the biological age of the individual when compared to the chronological age. The suggested association between cam morphology and osteitis pubis advocates a possible link with physical activity. If physical activity is likely to impact the accuracy of age estimations made at this area due to this condition, care must be taken when forming interpretations. Age estimation from the pubic symphysis is such a widely used method for both bioarchaeological study of past populations as well as forensic investigation, therefore further awareness of any condition which is likely to impact that accuracy of these assessments is important.

The current study has shown there are limitations to forming recording criteria which are easily reproducible for this condition due to the complex nature of the pubic symphysis and the various factors which impact the gross structure of this area. Additionally, the use of medical imaging to form criteria to be applied to skeletal specimens also presents challenges of its own.

9.5. Conclusion

This study has shown alpha angle size and cam morphology are associated with Poirier's facets, plaque type A and, to a lesser extent, plaque type B but not cribra. Through the use of contextual information, it is recommended this association is a functional adaptation. Additional osseous growth at the anterior aspect of the femur, in the form of these non-metric traits and cam morphology are likely to be adaptations to provide stability at the hip during skeletal maturation due to increased habitual activity or other extrinsic factors, such as terrain or increased loading at this joint. This study has shown occupational physical activity in adults does not have a significant impact on alpha angle size, therefore, caution should be exercised when using cam morphology to interpreting the levels of occupational activity within past populations. Cam morphology could, however be used as an indicator of high levels of physical activity prior/during skeletal maturation. It is therefore, suggested the difference in alpha angle size and cam morphology between males and females is due to combination of morphological differences in the pelvis between the sexes and, to a lesser extent, physical activity differences during childhood. Age did not appear to show a significant association with alpha angle size it is therefore suggested it remains consistent development.

No clear osseous indicators were found that can be used to determine if FAI, with cam morphology, is present/the hip is likely to become symptomatic. Therefore, without a clinical history, the results of this study suggest it is not possible to determine if an individual is symptomatic from osseous traits alone however the sample size of the FAI and non-FAI groups were small and further work with larger samples is required to clarify these results. Furthermore, no clear association between alpha angle size and osteitis pubis was shown. It is however suggested it may not be possible to identify traits of osteitis pubis on skeletal remains during the early stages of this condition.

Eburnation is a possible indicator of the later stages of this condition, as in osteoarthritis, however further study would be required to confirm this due to small sample numbers with this trait present.

These findings contribute to the disciplines of bioarchaeology by adding additional knowledge to the cause of non-metric traits of the femur, often recorded but rarely interpreted on skeletal remains. The association between non-metric traits and cam morphology allows a multidisciplinary approach to the understanding of these traits using a combination of clinical research and anthropological study. Additionally, cam morphology has not been fully addressed within bioarchaeology and potentially overlooked. This study therefore raises further awareness of this condition with the hope there will be continued research on further skeletal collections to allow comparisons between populations of different socioeconomic status, terrain, activity levels etc. to further understand contributing factors to its aetiology. The increased awareness of cam morphology and the ability to record it on bone, highlighted by this study, contributes to the discipline of forensic anthropology as an identifying feature, particularly if an ante-mortem record of FAI is present. These findings also contribute to these fields through contributions to the study of non-metric traits and physical activity-related pathologies from a different perspective. With one of the suggested factors associated with the development of cam morphology being physical activity during development, the ability to record this on skeletal remains would allow its use as a potential marker of activity (or other factors leading to stability at the joint) to learn more regarding levels of physical activity during childhood in past populations. The results of this study also encourage caution to be taken prior to using cam morphology as a marker of activity in adulthood. Finally, although the low error rates for the osteitis pubis data made it difficult to draw clear conclusions, contributions are still made through raising awareness of this condition, and its potential impact to age estimations methods focused on the pubic symphysis, within these disciplines.

9.6. Study limitations and future work

In this section the limitations which occurred during this study will be addressed. Where possible actions were taken to reduce these limitations however in some cases this was not possible. Any future work which could follow on from this research and these limitations has be recommended.

With regards to the alpha angle measurements, it was noted the placement of the circle around the femoral head to ensure “best fit” could introduce a level of subjectivity. Although the levels of inter- and intra- observer error were found to be very good there is a risk of error being introduced when this is performed manually. Additionally, a level of observer bias maybe introduced when recording alpha angles manually in relation to the presence of non-metric traits. Although, during the recording of alpha angles, the non-metric trait results were not made available and the orientation of the femur during these measurements did not allow clear visualisation of the anterior aspect of the femoral neck, there is the risk that manual recording could add a level of observer bias. The use and development of automated methods of measuring alpha angles and offset ratio would therefore reduce this limitation. Future studies could incorporate an automated method to perform these measurements to reduce this user bias.

The definition of physical activity levels in this study was also a limitation. Occupational activity was defined using MET values which have rarely been used within biological anthropology and therefore its accuracy as a measure of activity within this field has not been tested. In addition to this, it is not clear how transferrable this method is to past populations as the MET values were assigned using modern populations. In the current study, to alleviate the limitation of using a method developed from modern data to infer activity of past populations and to make the study comparable to other osteoarchaeological studies, method III was included. This method was used to categorise individuals as manual or non-manual using the database created by Perréard Lopreno and colleagues from previous studies of identified collections and with historical background information. MET values are also a measure of energy expenditure not biomechanical stress and therefore it is difficult to determine if this is suitable measure of loading placed on the joint for particular occupations. Future work analysing alpha angle size differences between occupations could categorise occupations based on primary limb loading e.g. occupations primarily focused on loading of the lower limb in comparison to the upper to determine if this has a significant impact on alpha angle size. Further to this, robusticity indices or cross-sectional geometry could be included in futures studies as the measures of physical activity to determine if there is a correlation between these measures and alpha angle size.

The use of occupational information from identified skeletal collections to categorise physical activity has limitations which are much debated in the anthropological literature and discussed in section 4.2.3.3. Perréard Lopreno et al. (2012) highlights many of these limitations including; representativeness of the sample, completeness and source of the occupation documentation (Perréard Lopreno et al., 2012). In addition to these limitations it is also difficult to determine activities that could impact physical activity levels, such as, recreational activity and long-term occupational profile. Other methods to determine physical activity, such as cross-sectional geometry, could also be tested in association with alpha angle size in future studies.

The observer error rates for this study was another limitation particularly regarding the osteitis pubis traits. To limit this in future, clear photographs of each trait being recorded should be provided, as well as additional training prior to recording. An additional cause of these error rates could also be due to the use of dichotomous traits to categories osteitis pubis and Poirier’s facets. These changes typically occur on a continuous scale and therefore the use of dichotomous traits may have limited this recording and added to the level of observer subjectivity. Future studies could therefore incorporate a larger scale for recording these traits with clearer descriptions.

The small sample size of the FAI-group and non-FAI group also limited the number of statistical tests which could be performed between these samples. The retrospective nature of this sample also meant limited context information was available for these individuals. Future studies could be performed with patients diagnosed with FAI and contextual information regarding occupation and recreational activities. This will provide more of an understanding to the cause of this condition and non-metric traits of the femur.

Although FAI is not a life-limiting condition some of the key conceptual challenges identified in the osteological paradox can be applied as limitations to this study. Wood et al. (1992) recommend the use of “simple societies” and focus on short-term use cemeteries to minimize the impact of heterogeneous frailty and demographic nonstationarity. This can also be applied to activity levels. The Wharram Percy collection sample used in this study represents a wide time so it cannot be assumed that the level and type of daily physical activity was consistent throughout the large time period (the assignment of phase was made through various methods including: radiocarbon dating, datable coffin fittings, stratigraphic relationships, burials from areas of church with radiocarbon dating and location of grave cuts). This is a limiting factor of this study and therefore future work could analyse the difference in alpha angle size between the different phases represented by this sample.

There was a non-significant increase in alpha angle size from 18-29 to 30-49 to 50+ years age range categories for both the Wharram Percy and Luis Lopes collections. The exact age data for the Luis Lopes collection also showed a small but not significant correlation between age and alpha angle size. This increase may be less to do with increase in risk of cam morphology but better explained by the osteological paradox. If cam morphology develops due to high levels of physical activity during skeletal development those individuals in the 18-29 years group represent those in the population who died at this younger age. Although the cause of death is not known, if an individual died at a younger age they are less likely to be involved in strenuous physical activity and therefore less likely to develop cam morphology. While the 50+ years group represents individuals who have a good enough level of health to reach these older ages. This is an inherent selection bias present in all bioarchaeological research due to the use of a sample of only the individuals who died at that age and not all individuals present in that population at the age during that time period. Further study on alpha angle size and age is therefore required.

Chapter 10. Appendices

Appendix 1 – Observations of osteitis pubis from the clinical imaging used to developed recording criteria

Author	Radiographic diagnostic observations for osteitis pubis
Phillips et al. (2016)	MRI and radiographs: • Osseous irregularity or fracture • Sclerosis • Bone marrow oedema • Fatty change • Osteophytes • Effusion • Capsular hypertrophy
Crockett et al. (2015)	Radiographs • Subchondral irregularity • Sclerosis • Osseous erosion • Widening of the pubic symphysis Chronic MRI findings • Subchondral cysts • Erosions • Articular surface irregularities • Joint widening • Stress fractures can occur if condition not recognised and managed
Angoules (2015)	Radiographs • Subchondral sclerosis • Symphyseal lytic changes • Widening or narrowing of the joint space • Subluxation or widening of the symphysis MRI

	• Bilateral or asymmetric subchondral plate bone marrow oedema from anterior to posterior Chronic phase MRI: • oedema may not be present • Periosteal reaction • Bone resorption • Irregular contour of articular surface • Osteophytes • Subchondral cyst
Hopp et al. (2013)	Radiographs: • Degenerative signs • Marginal irregularity • Erosions • Subchondral sclerosis of the pubic rami • Vertical instability MRI: • Pubic bone marrow oedema on one or both sides
Larson et al. (2013)	Radiographs: • Sclerosis • Lytic changes • Cystic changes MRI: • Parasymphyseal oedema
Friedman and Miller (2013)	Radiographs: • Sclerosis • Irregularity • Erosions of the pubic • Widening of the symphysis MRI: • Fluid in symphysis • Marrow oedema in the pubis extending across anterior posterior dimension • Secondary cleft sign
Budak and Oliver (2013)	Radiographs:

	• Normal • Subtle irregularity of the articular surface of the pubic symphysis • Gross erosion • Symphyseal widening • Subchondral cyst formation • Sclerosis • Osteophytic bridging MRI: • Subcondral marrow oedema within pubic bones • Irregularity of the symphyseal margin • Symphyseal fluid • Peripubic soft-tissue oedema • Symphyseal disk degeneration
Hackney (2012)	Radiograph: • Widening • Irregularity • Sclerosis of the margin • Accentuation of the origin of gracilis • Laxity of the joint
Beatty (2012)	Radiographs: • Sclerosis of the symphysis • With or without accompanying erosions and widening of the joint • Pubic symphysis instability and/or widening
Hiti et al. (2011)	Radiographs • Widening of the symphysis • Sclerosis • Rarefaction at the symphysis • Cystic changes • Marginal erosions in the subchondral bone • Pubic instability and widening CT: • Marginal stamp erosions of the parasymphyseal pubic

	• Insertional bony spur • Periarticular microcalcifications MRI: • Bone marrow oedema • Linear high T2 signal intensity in the parasymphyseal pubic • Fluid within the symphysis • Subchondral sclerosis • Subchondral resorption with bone irregularity • Osteophytosis • Pubic beaking • Secondary cleft sign
Kai et al. (2010)	Acute findings MRI: • Symmetric perisymphyseal hyperintensity on fluid-sensitive sequences – reflects diffuse subchondral bone marrow oedema Chronic findings MRI: • Bone irregularity • Subchondral sclerosis • Subchondral resorption • Osteophytosis
Koulouris (2008)	Radiograph: • Irregularity of the subchondral bone • Erosions • Fragmentation • Areas of osteopenia • Sclerosis • Widening • Symphysis undergoing accelerated degenerative changes MRI • Pubic bone marrow oedema shown as subchondral marrow hyperintensity on fluid-sensitive sequences • Subchondral cysts • Erosions

Cunningham et al. (2007)	MRI: • Paraarticular bone oedema, uni- or bilateral, identified remove from adductor attachment • Supportive feature of osteitis pubis included: • Paraarticular fatty marrow change • Articular surface irregularity • Stepoff • Inflammation in paraarticular soft tissue

Appendix 2 – Non-metric trait metadata

Table 10-1 Data for non-metric traits for the Wharram Percy Collection

Skel	Sex	Poirier's facets (L)	Poirier's facets (R)	Plaque (L)	Plaque (R)	Cribra (L)	Cribra (R)
CN06	m	0	0	3	3	0	0
CN07	f	0	0	0	0	0	0
CN11	m	0	0	1	0	0	0
CN14	m	0	0	1	0	0	0
CN16	f	0	NR	1	NR	0	NR
CN17	m	NR	0	NR	0	NR	0
CN18	m	0	0	2	1	0	0
CN20	m	1	1	0	0	0	0
CN24	m	0	0	0	0	0	2
CN27	m	0	0	2	2	0	2
CN28	m	0	0	3	0	2	0
CN30	f	0	0	0	0	1	1
CN32	m	0	0	0	3	1	1
CN38	m	1	0	1	0	0	0
CN40	f	NR	0	NR	0	NR	0
CN41	f	0	0	0	0	0	0
CN45	m	NR	0	NR	0	NR	1
EE003	m	0	0	2	1	0	1
EE013	m	0	NR	2	NR	2	NR
EE018	f	0	0	0	0	0	0
EE019	m	0	0	0	0	0	0
EE020	m	0	NR	1	NR	0	NR
EE043	f	0	0	0	0	0	0
EE070	f	0	0	0	3	2	2
EE080	m	0	0	2	0	1	1
EE085	m	0	0	0	0	0	0
EE099	f	0	0	0	0	0	0
G253	f	0	0	0	0	2	2
G254	f	0	0	0	0	0	0
G265	m	0	NR	0	NR	0	NR
G275	f	1	0	0	0	0	0
G278	m	0	NR	1	NR	0	NR
G297	m	0	0	2	2	0	0
G377	f	0	0	0	0	0	0
G385	f	0	0	0	0	2	0
G398	m	0	0	0	0	1	0
G406	m	0	0	0	0	0	0
G427	f	NR	0	NR	3	NR	0
G436	m	1	1	0	0	0	0
G462	m	0	0	1	0	1	2
G478	f	NR	0	NR	0	NR	0
G516	m	NR	0	NR	1	NR	0

G561	m	0	0	0	0	0	0
G582	f	NR	0	NR	0	NR	0
G604	m	0	NR	0	NR	2	NR
G607	m	0	0	1	0	0	0
G643	f	0	0	0	0	0	0
G652	f	0	NR	3	NR	0	NR
G694	m	0	0	1	2	0	0
G746	m	0	0	0	0	0	0
G747	f	0	0	0	0	0	0
NA047	f	NR	NR	NR	NR	NR	NR
NA066	f	0	0	0	0	2	2
NA075	m	0	0	1	1	1	0
NA094	f	0	0	0	1	2	0
NA102	m	0	0	0	0	0	0
NA104	m	0	0	3	3	1	1
NA121	m	0	0	2	2	0	0
NA128	m	0	0	0	0	0	0
NA140	m	NR	0	NR	2	NR	0
NA145	f?	0	0	3	3	0	0
NA157	f	0	0	2	2	0	0
NA166	m	0	0	0	0	0	0
NA167	f	0	0	0	0	0	0
NA170	f?	0	NR	0	NR	0	NR
NA173	f	0	0	3	3	1	1
NA176	m	0	0	0	0	0	0
NA181	m	1	1	0	0	0	0
NA183	m	0	0	2	0	0	0
NA195	m	0	0	0	0	0	0
NA199	m	0	0	0	0	0	0
NA218	m	0	0	3	3	0	0
NA224	m	0	NR	2	NR	0	NR
SA002	m	0	NR	1	NR	1	NR
SA012	m	NR	0	NR	2	NR	0
SA015	m	0	0	2	2	0	0
SA017	f	0	NR	0	NR	0	NR
SA017A	m	0	0	0	2	0	0
SA034	m	0	0	1	1	0	0
SA036	f	1	0	0	2	0	0
SA053	f	0	0	2	2	0	0
V38	m	0	0	2	0	0	0
V40	m	0	0	2	3	2	0
V42	m	1	1	1	1	0	0
V61	f	NR	0	NR	0	NR	0
WCO015	m	1	1	0	0	0	0
WCO017	f	0	0	0	0	0	0
WCO036	f	0	0	2	3	0	0
WCO037	m	1	1	0	0	0	0

WCO040	m	0	0	0	0	0	0
WCO056	f	0	0	0	0	0	0
WCO059	m	0	1	2	0	0	0
WCO062	m	0	0	0	0	1	1
WCO071	f	0	0	0	0	0	0
WCO078	m	0	0	3	3	0	0
WCO089	f	NR	0	NR	3	NR	0
WCO091	m	0	0	1	0	1	0
WCO093	f	0	0	0	3	0	0
WCO098	f?	NR	0	NR	0	NR	0
WCO109	f	0	0	0	0	0	0
WCO117	m	0	0	2	2	1	1
WCO122	f	0	0	0	0	1	1
WCO124	f	0	0	2	2	1	0
WCO125	m	0	0	3	0	0	0
WCO142	m	1	1	0	0	0	0
WCO146	m	0	0	2	2	0	0
WCO164A	m	0	NR	1	NR	0	NR
WCO174	m	0	0	3	1	0	0
WCO184	f	0	0	2	2	0	0
WCO200	m	0	0	0	0	0	0
WCO203	m	0	0	0	0	0	0

Sex: m = males, f = female, Poirier's facets: 1 = present, 0 = absent, Plaque: 0 = absent 1 = type A, 2 = type B, 3 = type c, Cribra: 0 = absent, 1 = type 1, 2 = type 2. NR = not recorded (bone absent or PM damage)

Table 10-2 Data for non-metric traits for the Luís Lopes collection

Skel	Poirier's facets (L)	Poirier's facets (R)	Plaque (L)	Plaque (R)	Cribra (L)	Cribra (R)
23	0	0	3	3	0	0
27	1	1	0	0	0	0
31	0	0	0	0	0	0
44	0	0	0	0	0	0
102	NR	0	NR	0	NR	0
127	NR	0	NR	3	NR	0
152	0	0	2	2	0	0
166	0	0	0	0	0	0
176	0	0	2	2	0	0
178	0	0	0	1	0	0
198	0	0	0	0	0	0
201	0	1	2	2	0	0
215	0	0	2	0	1	1
222	NR	0	NR	0	NR	0
233	0	0	1	1	0	0
236	0	1	2	0	0	0
239	0	0	0	0	0	0
242	0	0	3	3	0	0

244	0	0	2	1	0	0
245	0	0	2	2	0	0
270	0	0	3	3	0	0
272	1	1	0	0	0	0
273	0	0	0	0	0	0
299	0	0	0	0	0	0
301	1	1	1	0	1	1
302	0	0	1	2	0	0
305	0	0	0	0	0	0
310	0	0	2	2	0	1
313	1	1	0	0	0	0
318	0	0	0	0	2	2
324	0	0	0	0	0	0
329	0	0	0	0	0	0
332	0	0	3	3	0	0
339	0	0	3	0	0	0
341	0	0	0	0	0	0
344	0	0	2	2	1	0
345	0	0	3	0	0	0
346	1	1	0	2	0	0
373	1	1	0	0	0	0
383	0	NR	3	NR	0	NR
386	0	0	0	0	0	0
391	0	0	0	0	1	0
396	1	1	0	0	0	0
405	0	0	1	1	0	0
414	0	0	2	0	1	0
419	0	1	2	0	0	1
424	0	0	1	1	0	0
427	0	0	2	1	0	0
428	0	0	2	2	0	0
430	0	0	0	3	0	0
437	0	0	0	3	0	0
440	1	1	0	0	0	0
445	0	0	0	0	0	0
446	0	0	0	0	0	0
448	0	0	3	3	0	0
465	1	0	0	3	0	0
470	0	0	2	2	0	0
479	0	0	2	2	0	0
482	0	0	0	0	0	0
484	0	0	3	0	0	1
488	0	0	0	0	0	0
501	0	0	0	0	0	0
577	0	0	0	0	1	1
581	0	0	2	2	0	0

582	0	0	0	0	0	0
597	0	0	0	0	0	0
610	0	0	0	0	0	0
611	0	0	2	2	0	0
621	0	0	0	0	0	0
666	0	0	0	0	0	0
678	1	1	0	0	0	0
682	0	0	2	0	0	1
703	0	0	2	2	0	0
755	1	1	0	0	0	0
765	0	0	0	0	0	0
768	0	0	2	2	0	0
974	1	0	0	2	1	0
978	0	0	3	2	0	0
1043	0	0	0	0	0	0
1053	0	0	3	3	0	0
1081	1	1	0	0	0	0
1092	0	0	2	2	0	1
1095	0	0	2	2	0	0
1101	0	0	0	0	1	1
1139	0	0	0	2	1	1
1141	1	1	0	0	0	0
1168	1	0	0	0	0	0
1226	0	0	3	3	0	0
1249	0	0	2	3	0	0
1265	0	0	0	0	0	0
1279	0	0	2	2	0	0
1291	0	0	0	0	0	0
1297	0	NR	2	NR	0	NR
1299	0	0	0	0	0	0
1329	0	0	0	0	0	0
1335	0	0	0	0	0	0
1397	0	0	2	3	0	0
1414	1	0	0	2	1	1
1416	0	0	3	0	0	0
1444	0	0	2	2	1	1
1547	0	0	2	2	0	0
1613	0	0	0	0	0	0
1614	0	NR	0	NR	0	NR
1615	0	0	1	2	0	0
1617	1	1	0	0	0	0
1626	0	0	0	0	0	0
1636	0	0	2	2	0	0
1637	0	0	0	3	0	0

Poirier's facets: 1 = present, 0 = absent, Plaque: 0 = absent 1 = type A, 2 = type B, 3 = type c, Cribra: 0 = absent, 1 = type 1, 2 = type 2. NR = not recorded (bone absent or PM damage)

Table 10-3 Data for non-metric traits for the FAI and non-FAI groups

Case	Sex	Poirier's facets (L)	Poirier's facets (R)	Plaque (L)	Plaque (R)
C10	f	1	0	0	2
C11	f	0	0	2	3
C12	m	0	1	2	0
C13	m	1	1	0	0
C14	m	1	1	0	0
C15	m	0	0	1	1
C16	m	0	0	0	1
C17	f	0	0	1	2
C18	m	1	1	0	0
C19	m	1	1	0	0
C20	m	0	0	0	2
C21	f	0	1	0	0
C23	m	0	0	2	1
C25	m	0	0	1	2
C3	f	0	0	2	3
C4	m	0	0	0	1
C5	m	0	0	0	3
C7	f	1	1	0	0
PA0	f	0	0	2	1
PA1	m	0	0	2	2
PA10	m	0	0	1	2
PA11	f	0	0	0	0
PA13	f	0	0	2	3
PA2	m	1	1	0	0
PA4	m	1	1	0	0
PA5	f	0	0	2	0
PA6	f	0	0	0	1
PA7	m	0	0	2	0
PA8	m	0	0	2	2
PA9	m	0	0	1	2

Case: C = FAI group, P= Non-FAI group, Sex: m = males, f = female, Poirier's facets: 1 = present, 0 = absent, Plaque: 0 = absent 1 = type A, 2 = type B, 3 = type c,

Chapter 11. References

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