Subsistence Strategy and Tibial Shape: Identifying Variation in Activity Across the Sudanese Landscape

A thesis submitted for the degree of
PhD in Bioarchaeology
University College London

Stacy Hackner

Institute of Archaeology
University College London
31-34 Gordon Square
London WC1H 0PY

Declaration

I, Stacy Hackner, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

The growing human tibia is uniquely responsive to repeated activities, resulting in identifiable morphological patterns that can be applied to ancient populations. Much of the bioarchaeological research in this area focuses on the transition to agriculture, noting a decline in bone strength and robusticity with increasing levels of sedentism. However, not all human groups adopted agriculture simultaneously or uniformly, and there continues to be variation in subsistence strategy based on climate, resource availability, and cultural practice. In Sudan, groups have continued to practice nomadic pastoralism alongside agriculture, although sedentary agricultural societies tend to be the focus of most archaeological research in the region. This work examines the difference in tibial morphology between groups utilising different subsistence practices within the same geographic region and archaeological period to explore activity-based changes to the tibia, using both cross-sectional geometry and geometric morphometrics to quantify the difference between tibial cross-sectional shapes at midshaft. The results suggest that while clear differences exist in midshaft tibial shape between the Sudanese groups practicing differing subsistence strategies, there is no one shape that is indicative of nomadism or sedentism; rather, there are general trends indicating higher mobility among more members of the nomadic group and more local movement among the members of the sedentary groups. Further, there is more similarity between females of all groups than males, problematising the idea that all individuals respond to bone remodeling activity in the same way. The conclusions presented here recommend that more research needs to be conducted on tibial shape variation in Sudan and worldwide using geometric morphometrics, as it presents a more nuanced approach than cross-sectional geometry, and that bone remodeling in response to activity must continue to be explored in light of differences in age, sex, and musculature.

Table of Contents

List of Figures

List of Tables

Acknowledgements

This thesis would not have been possible without the help and support of many individuals. First, my supervisory team, Professor Simon Hillson (UCL), Dr Daniel Antoine (The British Museum), Dr Carolyn Rando (UCL), and Professor Tony Waldron are of key importance. Without Daniel's offhand comments on the need to investigate Nubian tibiae, I'd still be floundering. Dr Carolyn Rando deserves thanks and cake for her assistance both professionally and personally over the past few years; your support has literally been invaluable, particularly at crucial moments of writing up.

Thanks are also due to Dr Marta Lahr of the Duckworth Collection for providing access to the Jebel Moya collection and Sandra Bond for her help in securing a 3D scanner for the Institute and the computer that it needed to run, and for allowing me to hold onto it long after its due date.

A number of colleagues have provided assistance: Dr Tom Davies, who developed the AsciiSection program and helped me when it bugged; Dr Anna McGeachy for her help with R and mutual complaints; Dr Alison Macintosh for her advice on CSG interpretation; Bruno Vindrola for his help with ImageJ; Andrew Alexander for his help with mathematical dilemmas; Stephen Nash for statistical advice; Rob Kaleta and Dr Vincent Bonhomme for their assistance with Momocs. Rob has come to particularly hate my R questions, so apologies for the near-daily bother. Thanks to all the researchers who kindly provided their expertise and data, often in scans of decades-old notebooks – Dr Derek Welsby, Dr Stefano Biagetti, Dr Peter Copollilo, Dr Allan Morris, Dr Michael Brass, and Dr Amelia Moore.

Thanks to all my 322b colleagues – Liz Farebrother, Jennifer Tung, Bruno Vindrola, Tom Siek, Mariana Nabais, Eva Jobbova, Marion Hervé, and former office resident Dr Flip Ryan. You are the best research room, and have seen me in all my thesis-induced moods. I'd appreciate if you never told anyone how angry I became when I spent so long trying to work the wrong data file. Thanks to Chris Smith and Maike Pols from f1000 for providing a wonderful resource, and Katie Meheux for library assistance.

Final thanks go to all my family, friends both here and abroad, the community of Others, the student engagers and staff of UCL Museums, and everyone who put up with four years of complaints and the occasional yelp of success and provided funds, jobs, food, hugs, sympathy, and encouragement. This work is dedicated to my mom, Ruth-Anne Hackner, who proofread the entire document more than once.

1 Introduction

Bioarchaeological investigations of human skeletal remains have revealed that the shape of certain bones can indicate the activities performed by an individual. Exploring these differences in shape using human skeletons from ancient contexts can address questions of human behaviour and the human condition in the past, particularly differences between groups of individuals from different geographic regions or time periods (Larsen 2015). Biomechanical analysis of long bones demonstrates which parts of bone experienced stress from activity and has been increasingly used since the 1970s (Ruff and Larsen 2014). The theory that bone changes in response to activity was first posited in the late 19th century and now forms the basis for many studies within the field. Recent research investigating the particular ways in which bone responds to activity, including differences between age and sex groups and investigation of individuals practicing unique and repetitive activities, have shown that there are identifiable patterns of bone change that can then be applied to ancient groups (Haapasalo *et al.* 1998; Drapeau and Streeter 2006; Shaw and Stock 2009; Nikander *et al.* 2010). Previous examinations of the cross-sections of long bones have indicated that it is possible to infer general activity patterns for a group of individuals from an archaeological site. The upper limbs have been used to explore divisions of labour and unilateral activity (Rhodes and Knüsel 2005; Wanner *et al.* 2007; Pomeroy and Zakrzewski 2009), and mobility patterns have been explored through similar analysis of the lower limbs (Ruff 1987; Marchi 2008; Nikita *et al.* 2011; Shaw and Stock 2013). Both have been used to examine changes in activity patterns at sites worldwide.

Morphological change to long bones is used here to investigate differences in subsistence strategy in Sudan. Sudan has a varying climate with a number of ecological zones (Tothill 1948; Van Caenegem *et al.* 2012), allowing groups to practice nomadic pastoralism in rainier areas and sedentary irrigation-based agriculture in more arid regions along the Nile Valley. As the research referred to above primarily investigated longitudinal change, the groups of individuals selected for this study have archaeological dates spanning the Meroitic to Medieval periods (Ginns 2010b; Judd 2012; Brass 2015) to ensure that variation in long bone shape is the result of subsistence-related activity rather than a result of longitudinal change and decreasing activity. The bioarchaeological analysis presented here contributes towards understanding the differences between these agricultural and nomadic groups by examining activity. It will identify and quantify the difference in lower limb bone morphology between nomadic pastoralists and sedentary agriculturalists in Sudan between the Meroitic and Medieval periods. Further research should apply the methods presented here to pastoral and agricultural groups worldwide.

This research focuses on the tibia, or shin bone. While many studies focus on the femur, the tibia was chosen here because it is the primary weight-bearing bone of the lower leg and is aligned with the principal vertical axis of the body, which is important in assessing the response to load-bearing activity. Previous studies have found a stronger correlation between the tibia and mobility than the femur, which appears to be linked to body size and climate (Stock 2006; Marchi 2008; Macintosh *et al.* 2015). Research in this area has tracked changes in tibial morphology from the Paleolithic to the Industrial period, finding a general decrease in robusticity as well as a decrease in biomechanical properties indicating strength in response to compressive, bending, and twisting forces (Ruff and Hayes 1983; Marchi 2008; Macintosh *et al.* 2014). These differences in tibial cross-sectional morphology between time periods are often interpreted as indicative of differences in mobility. However, the transition to agriculture during the Neolithic has previously been described as “protracted” (Asouti and Fuller 2013). It is evident that there was variation in timing of the uptake of agriculture between different human groups. Therefore, it is erroneous to characterise an entire period as having one type of tibial morphology. In many regions, there have been (and still are) a mixture of groups practicing varying subsistence strategies, dependent on climate, political and cultural affiliations, and local resources (Bradley 1992; Cavalli-Sforza 1996; Fratkin *et al.* 1999; Turner 2004). The research project presented here also reveals a trend related to biological sex: differences in tibial morphology between females of different time periods appear to be less statistically significant than differences between males. This study seeks to investigate differences in tibial cross-section morphology with an emphasis on sexual dimorphism and variation in shape and the relation of these to subsistence practices for human groups in Sudan. Potential subsistence practices for human groups are then considered using this data. It uses the conventional biomechanical analysis of cross-sectional geometric properties and integrates a new geometric morphometrics-based approach to quantify differences in shape seen between groups.

The issues outlined above are explored in this work using the following structure. Chapter 2 details the anatomy of the leg, including bone features, musculature, and joint capabilities of the knee and ankle, and introduces the biomechanics of bone building and remodeling in response to activity. Chapter 3 discusses how activity has been defined and investigated archaeologically. As researchers often focus on labour instead of all activity, some valuable conclusions may be missed. Biomechanical and non-biomechanical markers of activity from sites around the world will be discussed to emphasise the variety of methods used in bioarchaeology as well as the varied goals of past studies. Chapter 4 reviews why the tibia has been an important bone to consider in past analyses of human behaviour, with examples of research on the tibia dating to the origins of anthropology and archaeology in the 19th century. Chapter 5 presents the research objectives and hypotheses of the project. Chapter 6 describes the material used and selection criteria, including a background of Sudanese archaeology. Chapter 7 details the methods used to address the research objectives presented in Chapter 5, with information on the specific metrics used. Chapter 8 presents the results of the data collection verbally and graphically. Chapter 9 interprets the results considering the current state of research into tibial morphology and biomechanics, discussing conclusions that can be drawn regarding ancient activity in Sudan. Finally, Chapter 10 concludes the thesis by summarising the results and presenting avenues for future research.

2 Anatomy and Biomechanics of the Lower Leg

This chapter discusses the biology and anatomy of the human lower leg, providing a background on the use of lower limb biomechanics to address archaeological questions. The first half of the chapter reviews the bones, joints, muscles, and fascia of the lower leg, discussing how they articulate and function in human bipedal weight-bearing motions. Initially, biomechanics is defined as the study of the forces acting within the body and on the body (Hall 2012); this definition will be further clarified using specific examples within each section. The second half of this chapter presents biomechanics research and its current applications. It explains the purpose of the field, the types of research, and why biomechanics can be applied to bioarcheology. Biomechanics of human limbs is the key focus, although biomechanical studies of the entire body or other animals are referenced.

2.1 Bone structure and development

The tibia and fibula comprise the bones of the lower leg. The anatomy of each bone will be reviewed here, and will introduce the morphological features relevant to the study of biomechanics. The general shape, structure, and variation of these bones must be known in order to discuss their capacity to change in response to stimuli. The focus of this section is on the tibia and fibula; for anatomy of other skeletal elements, see Drake *et al.* (2010), Netter (2006), Dauber and Feneis (2007), and Hall (2012). The basic elements of the tibia and fibula described in this section are illustrated in Figure 2.1.1.

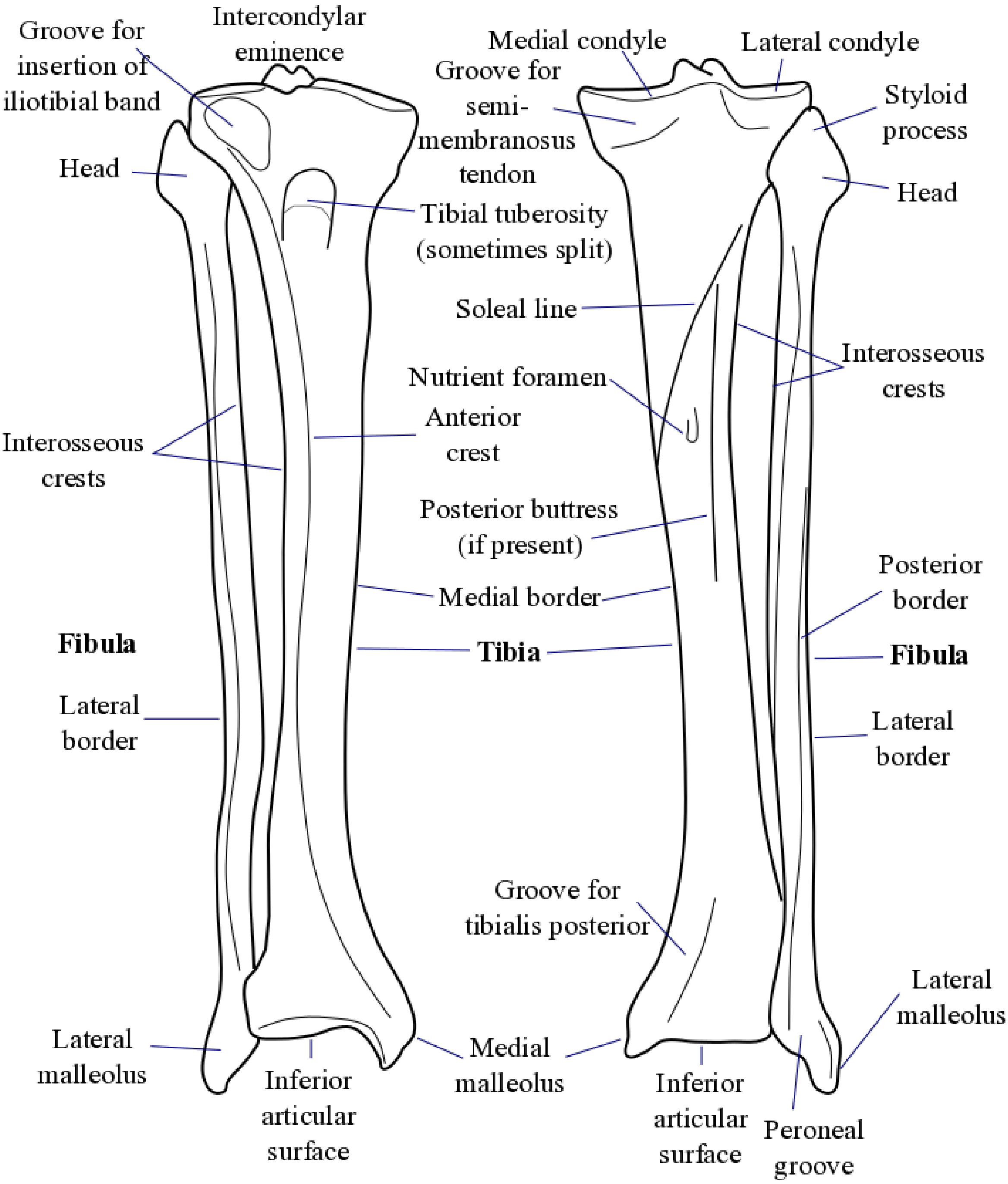


Figure 2.1.1 Illustration of the major features of the tibia and fibula. An anterior view is shown on the left and a posterior view is shown on the right. S. Hackner 2016.

2.1.1 The tibia

The tibia is a weight-bearing bone, situated towards the anterior and medial side of the leg. It is the second-largest and second-longest bone in the body. The condyles of the femur transfer the full weight of the body through the meniscal cartilage onto the plateaus of the tibia, with only a small amount of weight transferred to the fibula during movement. The tibia articulates twice with the fibula, proximally with the femur, and distally with the talus (Drake *et al.* 2010: 586). The tibia's proximal surface is divided into the oval medial and circular lateral condyles, each of which has an articular eminence (or plateau). Between them is the intercondyloid eminence, or spine of the tibia, which anchors the ligamentous attachments of the knee (see Figure 2.1.2). The distal end of the tibia has a quadrilateral articular surface and is bordered medially by the pointed medial malleolus (Drake *et al.* 2010: 586).

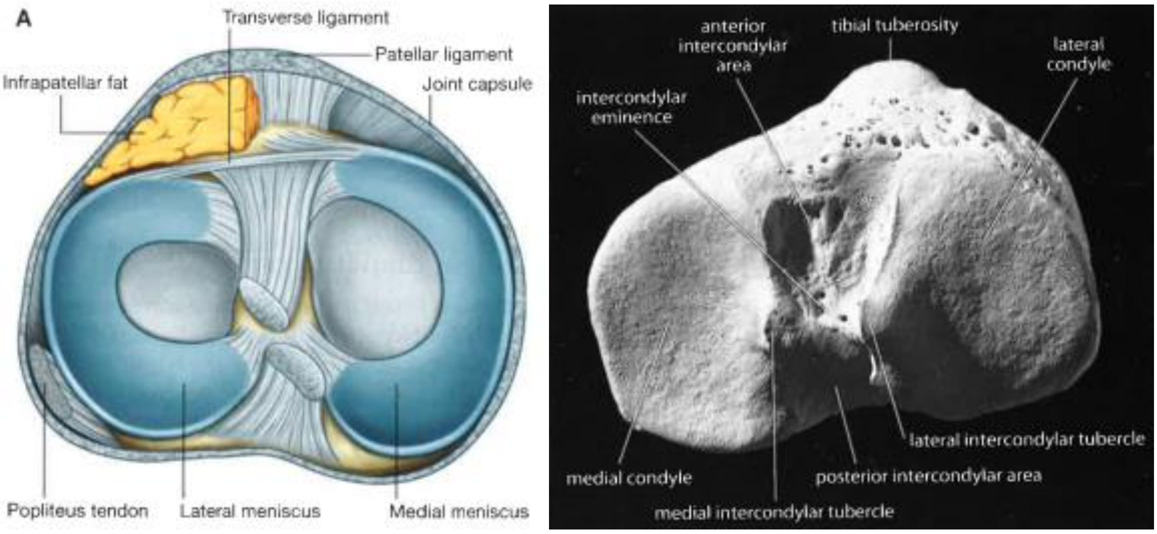


Figure 2.1.2 The proximal articulation of the tibia, illustrated with menisci and ligaments covering the tibial condyles and intercondylar eminence (left, as taken from Drake *et al*. 2010: 576) and without, exposing the bone surface (right, as taken from White *et al*. 2012: 260).

Viewed from the anterior, the tibial shaft has an hourglass shape and a slight S-curve of the anterior crest to the lateral and then medial; viewed in cross-section, the majority of the shaft is roughly triangular, becoming very thin and almost round at the distal end before widening for the distal epiphysis. The triangular shape of the shaft is due to the sharp anterior crest, the interosseous border, and the medial border (Drake *et al*. 2010: 587).

However, the tibial shaft shape in cross-section shows variation; this is discussed below in Section 2.7.2 and Chapter 4.

The tibia ossifies from three centres and is later joined by a fourth, the tibial tuberosity. The primary centre, the diaphysis, begins to ossify at 8 fetal weeks; at 20 fetal weeks, all skeletal structures around the knee and ankle are recognizable (Scheuer and Black 2000: 360). The proximal epiphysis ossifies shortly before birth and is seen in 95% of 3-month-olds; it continues to develop to full size until age 11-13, at which point the facets for the fibular articulation and iliotibial bands (see below) can be seen clearly. Fusion commences with “cessation of growth in height” (Scheuer and Black 2000: 364), and can occur from 13-14.5 years in females and 15.5-17 years in males, although some studies estimate complete fusion to only occur around 17 and 19 years respectively. The distal epiphysis begins ossification during the first year but only becomes recognizable around 3-4 years (Scheuer and Black 2000: 364). It changes size and shape until puberty and begins fusion around 12-13 years in females and 14-15 years in males. Although fusion is often complete at 14.5 years and 16.5 years respectively, it can continue until age 20 (Scheuer and Black 2000: 367).

The tibial tuberosity begins as an outgrowth from the proximal epiphysis at the 4th fetal month that gradually separates from the main body by an area of fibrovascular tissue. Ossification continues proximally from one or more centres between 8-12 years in females and 9-14 years in males. Fusion is variable but generally occurs around 14.5 years in females and 16 years in males, beginning at the proximal end (Scheuer and Black 2000: 365). Due to this irregular fusion, overexertion of the leg muscles during adolescence can lead to Osgood-Schlatter disease (OSD), resulting in pain, swelling of the patellar tendon, and abnormal fragmentation of the developing tuberosity (Maher and Ilgen 2013; Mayo Clinic Staff 2011). In some cases, lack of treatment results in excessive ossification and the tuberosity ossifies as a different shape or as *genu recurvatum* (Antich and Brewster 1985). One study found that among athletes with OSD, the pain began at an average of 13.1 years and affected males and females equally (Kujala *et al.* 2000); previously it was thought to affect more males than females, but this has changed since more women and girls participate in sports and heavy exercise. It is thought to occur in athletes participating in sports involving kicking, running, jumping, and squatting; Mayo Clinic suggests soccer, American football, and basketball, which are among the most popular sports for American youth (Mayo Clinic Staff 2011). OSD may be a possible explanation for some of the displaced tuberosities seen in previous Nubian study groups (Hackner 2012), but as the literature only reviews clinical cases and does not examine sufferers' knees postmortem, it was not possible to make a discrete diagnosis.

2.1.2 The fibula

Although this study does not examine the fibula as those from the three Sudanese sites were highly fragmented, it is important to discuss its anatomical function, as the tibia and fibula articulate and share weight-bearing when in motion. The fibula is a long, thin bone positioned in the lateral part of the leg. The cross-section of the diaphysis varies widely in shape from circular to roughly triangular to semilunar. It articulates proximally with the tibia and distally with the talus and tibia (Drake *et al.* 2010: 586), and is generally situated posterolateral to the tibia. The developmental analogue to the radius, it serves as a site of muscle attachments to stabilize the tibia and can bear from 7-17% of the compressive load on the lower extremity. However, it is likely that the fibula usually supports a much lower percentage of the full body weight, and that its primary purpose is ankle stability during dorsiflexion; Takebe *et al.* (1984) found that it supports only 6.4% when the ankle is in a neutral position, although recent work by Fazlollah *et al.* (2015) indicated that this may vary due to fibular location in relation to the tibia. A cadaver biomechanical study found that the fibula provided torsional stability to the knee and ankle, and resection of fibulae resulted in tibial fractures (Thambyah and Pereira 2006). Recent studies by Fazlollah *et al.* (2014; 2015) showed that the position of the fibular centroid relative to the tibial centroid may influence fibular rigidity: as the fibula approached the coronal plane, its bending rigidity increased, possibly acting as a mediator for load sharing with the tibia, allowing this body segment to take on additional weight. Additionally, this varied by sport when athletes were examined. In long distance runners, a positive correlation was found between tibial mediolateral bending rigidity and distance from the fibula, while for cricketers and hockey players, a positive correlation was found between tibial mediolateral bending rigidity and increase in angle between the centroids (Fazlollah *et al.* 2014). It was unclear, though, whether increased tibial rigidity is dependent on fibular angle and distance or vice versa. Marchi's work reviews previous authors who argue that talcrural angle, talocrural articular surface size, and varus and valgus knee positions reflect habitual force, allowing the fibula to be used to examine bipedal motion (2007: 648). The placement of the fibula in relation to the tibia thus both determines and is determined by external forces, which then act alongside other muscular and membranous forces, which will be discussed later in this chapter.

2.2 Joints: the knee and ankle

A discussion of the tibial diaphysis is incomplete without full comprehension of the joints and joint surfaces proximal and distal to it: the tibia does not exist in isolation, and is connected by numerous muscles and ligaments to the femur, patella, fibula, and talus. The anatomy of the knee and ankle joints and their role in lower leg biomechanics will be discussed here. Further information on the surrounding bones, including the upper leg and foot, can be found in Drake *et al.* (2010), Netter (2006), and Hall (2012). For the purposes of this project, the following discussions will focus on the tibia and surrounding joints, whilst understanding that these do not operate in isolation from the entire skeletal system. Where relevant, other skeletal elements will be included.

2.2.1 The knee joint

The knee is the largest joint in the body, and "alarmingly complex" (Lovejoy 2007; Herzmark 1938); in humans, the femoral and tibial condyles are larger than other apes, providing maximum stability while walking upright, which requires full joint extension (Herzmark 1938: 77). Lovejoy further described the knee's complexity, shown in Figure 2.2.1, as:

> "[…] essentially two noncongruent rigidly-paired 'balls' perched atop corresponding virtually frictionless meniscal-lined 'sockets'. The 'balls' effectively constitute a cylinder whose position is stabilized by its musculotendinous sheath, its menisci, and its four principal ligaments. These must

> be attached in fairly close proximity to the joint's principal axis of rotation, roughly near a line connecting the medial and lateral femoral epicondyles" (Lovejoy 2007: 326).

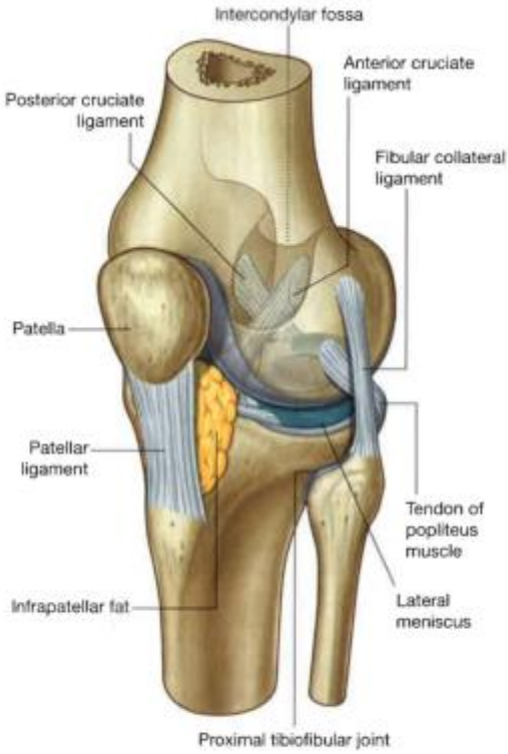


Figure 2.2.1 An illustration of the knee joint, showing the tibia, fibula, femur, patella, menisci, fat pad, and intracapsular ligaments, as taken from Drake *et al.* (2010: 576).

The knee is a synovial hinge joint in three parts, comprising the tibia, femur, and patella. It is actually two joints, the patellofemoral and tibiofemoral, acting as a hinge and a pivot and allowing six degrees of freedom (Trilha Juniour *et al.* 2009; Paasuke 2011), shown in Figure 2.2.2.

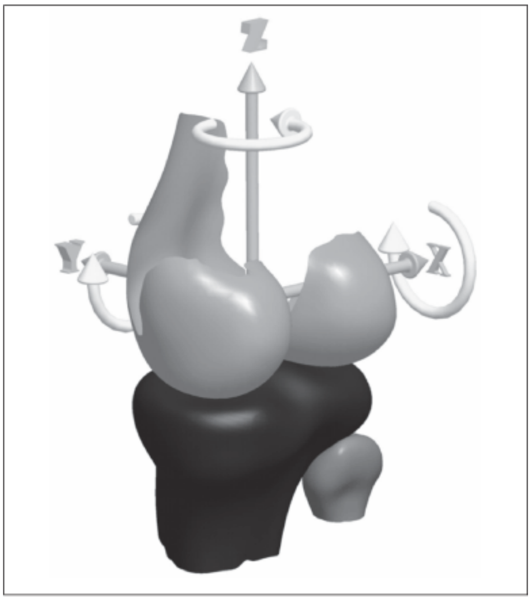


Figure 1 – *Knee movements.*

Figure 2.2.2 Virtual model showing six degrees of freedom of the knee. Flexion/extension occurs around the coronal (x) axis; medial/lateral translation and adduction/abduction occurs around the sagittal (y) axis; upper/lower and internal/external translations occur around the transverse (z) axis, as taken from Trilha Juniour *et al*. (2009: 18). The patella is not shown here.

The primary movement of the knee is flexion/extension (movement in the sagittal plane); the other movements are upper/lower translation (movement of the bones across one another), mediolateral translation, internal/external rotation (movement around a midline), and adduction/abduction (movement in the coronal plane). A non-pathological knee can experience up to 160° flexion and 5° extension; translation can be 5-10 mm anteroposteriorly, 1-2 mm mediolaterally, and 2-5 mm in compression (Paasuke 2011: 7). The act of walking on a flat plane involves posterior translation of the femoral condyles before flexion of the joint. Knee flexion is subdivided into three arcs. The "passive deep-flexion arc" occurs from 120-140° and is the result of external forces (body weight) increasing flexion. In passive deep-flexion, the medial femoral condyle rises up ~2 mm while moving posteriorly, and the lateral condyle lowers ~2 mm and subluxes off the tibia (Williams and Logan 2004: 84). The "functional active arc" occurs from 20°-120° and does not necessarily involve rotation, although this can be voluntarily controlled. The final 20° of flexion to full extension (either 0° or hyperextension) in a movement is called the "screw-home arc", involving the medial femoral condyle lifting 1-2 mm and the lateral femoral condyle rotating internally and towards anterior as full extension is reached (Williams and Logan 2004: 84). Due to the complexity of condylar curvature and individual variation, some knees are more stable in full extension than others (Hall 2012: 239). Average degrees of flexion vary between activities, but walking on a flat surface flexes the knee up to 60°, stair-climbing 80°, rising from a toilet seat 115° (Paasuke 2011: 132), and squatting 142° (Thambyah 2008: 290). In forward motion, the tibia remains stable on an anterior-posterior plane, although in extreme flexion the femoral condyles are translated posteriorly up to 22 mm (Johal *et al.* 2005; Chen *et al.* 2014). Further research into knee kinematics using CT scanning has shown that there is more rotation of both the femur and tibia than expected by anatomical researchers in the 19th century (Freeman and Pinskerova 2005). The tibia's rotation relative to the femur is possible only when it is not bearing weight, and can rotate to the greatest extent when the knee is flexed to 90°. Additionally, the knee can adduct and abduct, but generally only in response to externally applied forces (Hall 2012: 244).

The knee has a medial and lateral component where each of the tibial condyles meet the femoral condyles, articulating flexion and extension of the leg; the patella, while not articulating with the tibia, still forms an extension, the third part – the patellofemoral joint. The patella itself is the largest sesamoid bone in the human body, and is fully encased within the *quadriceps femoris* tendon; its likely purpose is to increase the leverage that the tendon can exert on the joint by increasing the angle in extension, improving the mechanical advantage of the knee by up to 50% (Herzmark 1938: 79; Hall 2012: 241). A lax synovial membrane encases the knee joint, covering all articular surfaces, and six bursae – three intracapsular and three extracapsular – provide additional cushioning and reduce friction during movement (Hall 2012: 241). Knee ligaments are separated into those that are intracapsular and those that are extracapsular (Kirshner *et al.* 2015). Within the knee, there are a number of soft-tissue structures and ligaments vital to smooth and efficient joint operation. First, each condyle is cushioned by a large crescent-shaped meniscus, a fibrocartilage pad that absorbs shock, distributes load – up to 45% of the total, - and provides lubrication for the joint, in addition to the fluid-filled bursae (synovial sacs) within the joint and the articular cartilage protecting each articular surface (Kirshner *et al.* 2015).

The two menisci are connected by a transverse ligament on the anterior side, and the medial meniscus is directly attached to the medial collateral ligament (Hall 2012: 240).

Second, the knee encases many ligaments that allow freedom of movement while providing stability. Inside the joint capsule, two cruciate ligaments cross each other within the joint: the anterior cruciate ligament connects the anterior proximal edge of the tibia to a slightly more lateral surface within the intercondylar fossa and prevents forward motion of the tibia, and the posterior cruciate ligament connects the posterior proximal tibia to a slightly more medial surface within the intercondylar fossa and prevents backward motion of the tibia, appearing crossed from a lateral view, shown in Figure 2.2.3 (Kirshner *et al.* 2015; Drake *et al.* 2010: 581). These ligaments are smaller and cover less joint surface area than in other apes and quadrupeds, possibly indicating that they are vestigial (Herzmark 1938: 84). These ligaments are twisted in such a way so that at each point in the flexion-extension cycle, each portion is sequentially taut, reducing overall strain (Lovejoy 2007: 326); they limit anteroposterior sliding during flexion as well as limiting hyperextension (Hall 2012: 241). Outside the joint capsule, either side of the knee joint features a collateral ligament: the medial collateral attaches the medial femoral condyle to the medial tibial condyle, and the lateral collateral attaches the lateral femoral condyle to the proximal fibula. Two other extracapsular ligaments, both posterior to the knee, are the arcuate popliteal ligament and oblique popliteal ligament; the former connects the intercondyloid fossa to the posterior margin of the head of the tibia, and the latter connects the posterior head of the fibula with the lateral femoral condyle, passing over the *popliteus* muscle (Netter 2006; Drake *et al.* 2010: 579).

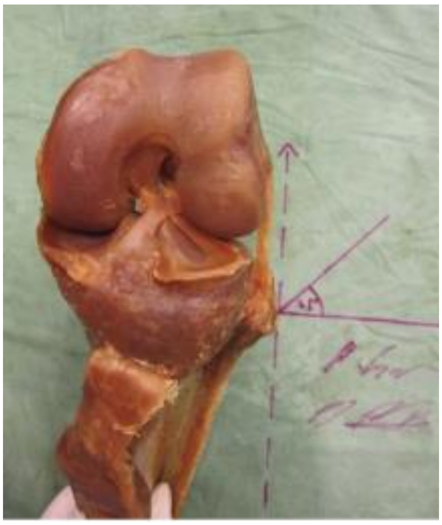


Figure 2.2.3 The anterior and posterior cruciate ligaments can be seen in this dissected cadaveric knee, as taken from Sadoghi *et al*. (2012: 1772).

The knee joint can be described in terms of the tibiofemoral and bicondylar angles. The tibiofemoral angle begins as a varus angle at birth (in a study of Nigerian infants, the average angle was 13.2° ± 3.8°) and gradually develops into a valgus angle (in the same study, -7.7° ± 2.2° at 36 months), changing from varus to valgus between 18-19 months, with an apparent worldwide standard deviation of 6 months (Oyewole *et al.* 2013). The authors note that independent walking began at approximately 12 months, earlier than the valgus angle developed; however, the angle development may be accelerated by walking, as seen with the bicondylar angle above. These joint angles do not develop independently, but rely on independent bipedal walking in order to develop concurrently. Figure 2.2.4 shows the bicondylar angle in a scanned cadaveric section.

Figure 2.2.4 The tibiofemoral angle shown in a scanned cadaveric section, as taken from Freeman and Pinskerova (2005: 202).

In a neutral stance, the tibia can be assumed to hold at least 90% of total body weight. The femur, directly proximal, carries the totality of the body's weight, but is angled in the body due to the compromise between maximum stability and pelvic width. This difference in angulation between the femur's maximum length in an imaginary vertical plane and true physiological length in which both condyles rest on the tibia, known as the bicondylar angle, is associated with bipedalism (Shefelbine *et al.* 2002; Trinkaus and Ruff 2012). The average modern human bicondylar angle ranges between 8-12°, trending slightly lower for males due to longer femurs and shorter interacetabular distances than females (Lovejoy 2007), while that of a non-bipedal ape such as the chimpanzee is 1-2°; the earliest known human ancestor with a notable bicondylar angle is *Australopithecus afarensis*, with an angle of 12-15°, demonstrated in Figure 2.2.5. It should be noted that bicondylar angle in humans decreases to 5-8° during flexion due to varying degrees of internal rotation, although some angle remains unlike in primates where the angle reduces to zero in flexion (Shefelbine *et al.* 2002; Lovejoy 2007).

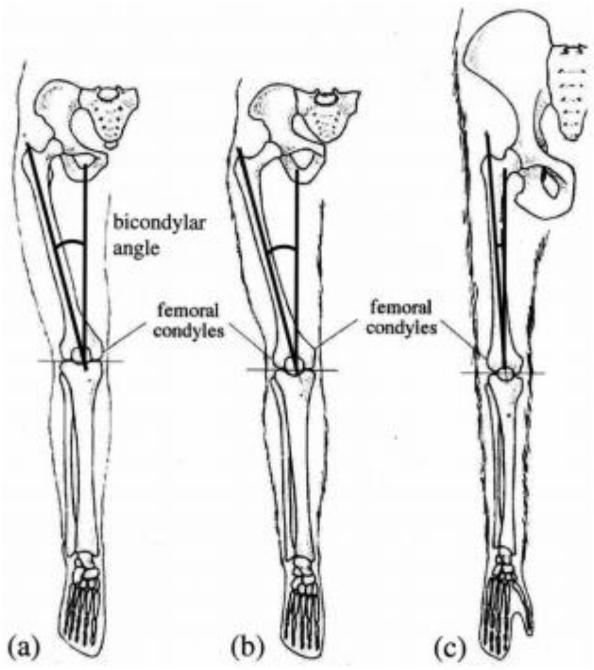


Figure 2.2.5 The femoral bicondylar angle, as taken from Shefelbine *et al.* (2002: 765). **(a)** is a modern human, (**b)** is *Australopithecus afarensis,* and (**c)** is *Pan troglodytes.* The higher angle in australopithecines is thought to be due to shorter femurs and greater interacetabular distance, similar to modern human females.

The bicondylar angle affects the femur biomechanically as any compressive load placed on it is torsional as well as longitudinal. In fact, Shefelbine *et al.* (2002) identified that the bicondylar angle is not present in neonates and fails to develop in bedridden children, indicating that it is formed through the biomechanical processes of bipedal walking. In a predictive computer model, high loading on the medial femoral condyle during the single-leg stance of a gait resulted in lateral angulation of the femoral shaft and thus a 10° bicondylar angle by the age of 8, given average growth rates (Shefelbine *et al.* 2002).

Lovejoy (2007: 329) described the human leg as tibia-dominant when compared with the chimpanzee leg, which is patella-dominant. Compared to chimpanzees, modern humans have a sagittaly-elongated lateral femoral condyle, resulting in a longer contact period and thus lower forces during extension and a more complex, angulated patella resulting in lower patellofemoral contact and higher patellofemoral stress in flexion (Figure 2.2.6). This is due to the longer patellar movement arm, which in turn reduces the force required by the quadriceps tendon. The shared joint region is more complex in humans, with the femoral condyle mirroring the concavity of the meniscus. These differences in the bone are also reflected in meniscal shapes and position of cartilaginous attachments: humans have "substantially greater cartilage contact during the last 20° of extension [the screw-home arc], which reduces overall stress from ground reaction during toe-off and heel strike" (Lovejoy 2007: 329).

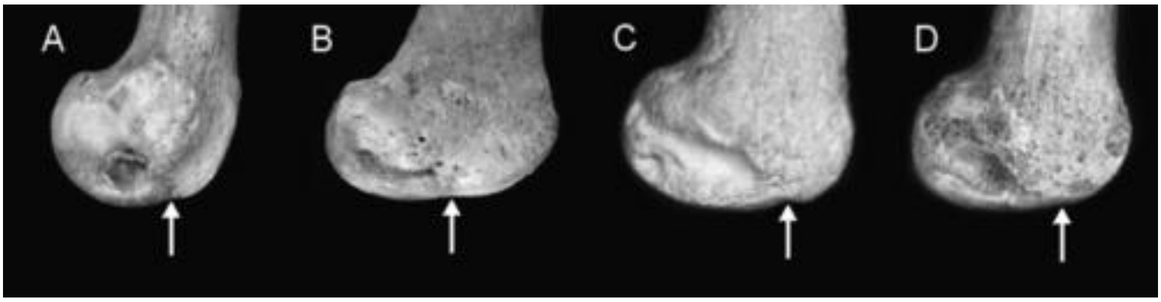


Figure 2.2.6 The distal femur (lateral view) in **A** *P. troglodytes*, **B** modern human, **C** and **D** *A. afarensis*: note condylar elongation in hominins. As taken from Lovejoy (2007: 330).

From a weight-bearing perspective, the force exerted on the lower leg by the knee joint must be examined. The knee primarily experiences compression and shear forces, as it is located between the human body's longest two levers. The stance phase of gait has been reported to elicit a compressive force on the tibiofemoral joint of 3x body weight and 4x body weight climbing stairs (Hall 2012: 244). Squatting, an activity that results in maximum joint flexion and contact area of 150 mm^2, has been shown to elicit a tibiofemoral force of up to 7.3x body weight, although some studies have shown it to be only 2.8-3.8x. This could be due to a difference in squatting posture: higher forces were measured in individuals who elevated their heels as opposed to placing their feet flat (Thambyah 2008: 287), which is the more common position adopted by cultures that habitually squat, and the force may be reduced due to the calf supporting the thigh during peak flexion. The tibiofemoral load is distributed across the medial and lateral tibial condyles at different phases of the gait; as the medial condyle is 60% larger than the lateral and has a thicker meniscus, it is able to absorb larger stresses (Thambyah 2008: 287). The patellofemoral joint experiences slightly different forces. A study of the patellofemoral joint reaction force showed that walking on a level surface results in forces .5x body weight, while climbing stairs results in a force of 3.3x body weight and doing squats results in a force of 7.6x body weight (Reilly and Martens 1972: 136; Hall 2012: 245); however, these results are not comparable to other studies which present forces in Newtons/kg-bodyweight and are much more specific with regard to subject's sex and body mass. Chen *et al.* (2010: 422) found the patellofemoral joint reaction force to be 10.1 N/kg-bwt for walking, 27.9 N/kg-bwt for descending stairs, 26,7 N/kg-bwt for climbing stairs, and 58.2 N/kg-bwt for running, with males and females differing only .2 N/kg-bwt in walking but 4.6 N/kg-bwt in climbing stairs; the authors do not explain why this force would be sexually dimorphic.

§§§2.2.2 The ankle joint

The ankle, or talocrural, joint is comprised of three bones: the distal tibia, the distal fibula, and the talus. These are divided into three separate joints: the distal tibiofibular, tibiotalar, and fibulotalar joints. However, the tibia and fibula form a syndesmosis or only slightly mobile joint bound by fibrous tissue, and most motion occurs at the tibiotalar joint (Hoagland 2015). The ankle can plantarflex and dorsiflex as well as turn medially and laterally around the fibula; when combined with calcaneal and navicular joint movements, it creates a universal complex joint (Drake *et al.* 2010: 605; Netter 2006). All three joints within the ankle complex are encased in a joint capsule that is thicker on the medial side and thinner on the posterior side (Hall 2012: 251).

There are eight major ligaments within the ankle complex, five of which originate from the distal tibia (Drake *et al.* 2010: 606). Three of these - the anterior and posterior talofibular and the calcaneofibular - stabilize the lateral part of the joint and do not originate at the tibia. In dorsiflexion and plantarflexion, each of these ligaments is alternately taut or loose. The anterior tibiofibular ligament has a lower load to failure than the cord-like calcaneofibular ligament by 2-3.5 times, but the former can undergo significantly more deformation as it allows for internal rotation of the talus (Hoagland 2015). Medially, the superficial deltoid ligament and deep deltoid ligament both prevent abduction and act as a secondary restraint against anterior translation; the greatest mechanical forces on the ankle are medially-directed during normal external rotation during walking and running (Hoagland 2015). Within the distal part of the tibiofibular syndesmosis arising from the interosseous membrane, there are three more ligaments: the interosseous ligament, the anteroinferior tibiofibular ligament, and the posteroinferior tibiofibular ligament. Each of these contributes to ankle stability in varying quantities, with the anteroinferior and posteroinferior accounting for around 70% (Attarian *et al.* 1985; Ogilvie-Harris *et al.* 1994). Cadaveric resection has shown that these syndesmotic ligaments account for very little stability when the other ligaments are intact, but this has little impact on living humans as injuries to the syndesmosis always occur in concert with injuries to the lateral or medial ligaments (Hoagland 2015). As in the knee, some variation in ligaments occurs, which can result in increased or decreased flexion (Trouilloud *et al.* 1988). Two additional ligaments cross the dorsal surface of the foot and ankle to hold tendons in place: the superior and inferior transverse retinacula (Netter 2006).

Ankle joint movement is primarily frontal-oblique in the sagittal plane, although the orientation changes slightly as rotation occurs. In non-loadbearing motion, the articular surfaces can slide against each other without appreciable deformation (Hall 2012: 252). In a full range of motion from plantarflexion to dorsiflexion, the lateral and medial malleoli separate by up to 1.5 mm, and the tibia can rotate on the talus up to 6° (Hoagland 2015).

While hip and knee functions in biomechanics have been studied extensively, the evolution of the ankle with regard to bipedalism is less understood. There are considerable differences between the ankles of hominins and apes. In the former (specifically, “Lucy”), the talar groove for the *flexor hallucis longus* is oriented vertically so that in extreme flexion, the most inferior margin of the tibia is in contact with both talar tubercles (Latimer *et al.* 1987). In gorillas and chimpanzees, this groove is oriented obliquely. An examination of an *Australopithecus sediba* ankle joint by Zipfel *et al*. (2011) revealed the same similarity to the modern human ankle as well as joint surface angle; both of these features indicate the presence of a valgus knee, discussed above, and thus bipedalism. When examining the angle of rotation, all hominoids have uniaxial rotation but the angle differs significantly (Latimer *et al.* 1987; Isman and Inman 1969). The vertical midline of hominin tibia and fibula are perpendicular to the articulation with the talus, while the pongid tibia and fibula are laterally angled up to 110°, shown in Figure 2.2.7.

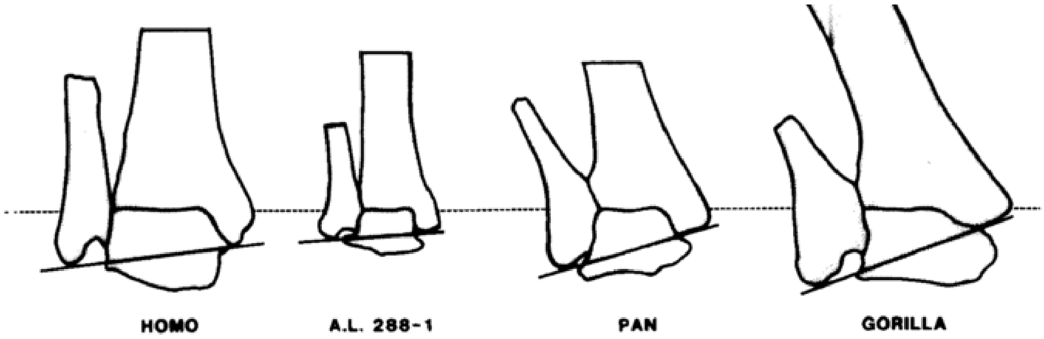


Figure 2.2.7 From left, human, *Australopithecus afarensis* "Lucy", chimpanzee, and gorilla ankle joints, as taken from Latimer *et al.* (1987: 162).

These differences are correlated with the angle of the knee and hip: a distinguishing feature of the human gait is parallel legs as opposed to the wide-legged stance of pongids. Examination of the ankle and knee joints is crucial to understanding hominin bipedalism, and the tibia enables researchers to examine both.

A feature that occasionally appears on the tibia at the ankle joint is the squatting facet or facets. These are extensions to the tibiotalar joint surface on the anterior side. Matching facets can be seen on the dorsal talus, sometimes extending to the trochlear surface. Recorded as a nonmetric trait in Bass (2004), it is unclear whether the presence of squatting facets is due to genetic variation of the joint surface or is acquired through squatting behavior during growth; if the latter, squatting facets could be an additional indicator of activity, though early 20th-century authors report finding these facets on fetuses and infants in Asian populations (Trinkaus 1975). The presence of squatting facets of fetuses may be due to hyperdorsiflexion of the ankle in utero, particularly after 20 weeks gestation (Boulle 2001b: 347). These could continue to be seen postnatally, but a lack of hyperdorsiflexion during growth and adulthood could cause the capsular ligament to obliterate them, leading to a higher frequency of facets observed in infants than in adults (Boulle 2001b: 348). Squatting, discussed briefly in section 2.2.1, is a position of hyperflexion of the knee and hip and hyperdorsiflexion of the ankle, shown in Figure 2.2.8. The position can be altered by raising or lowering the heels, which increases or decreases force at the knee respectively.

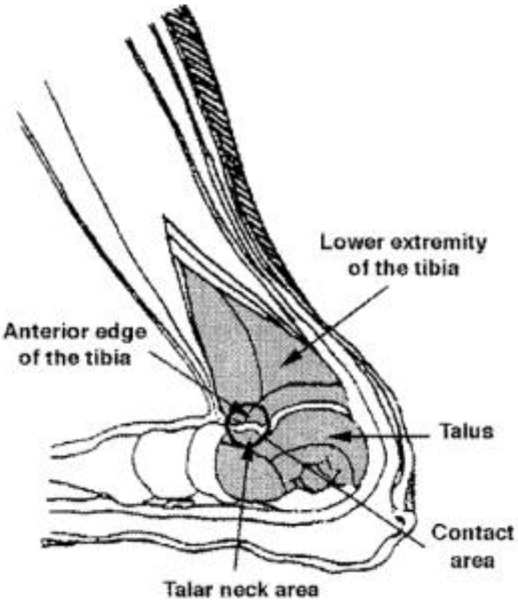


Figure 2.2.8 Diagram of the lower leg and foot showing hyperdorsiflexion of the ankle in the squatting position, indicating points of contact between the tibia and talus. As taken from Boulle (2001a: 51).

As Trinkaus (1975: 328) explains, enlargement of the articular surface would be an adaptive response to high pressure on the joint, although for most articulations this is seen as circumferential enlargement or facet fusion. The process may also be age dependent: increased pressure later in life may result in eburnation, bone cysts, or osteochondritic lesions.

Squatting facets on the tibia and talus are divided into two types: medial and lateral (Oygucu *et al.* 1998: 287; Boulle 2001a: 51), shown in Figure 2.2.9. Evidence of squatting is understood to be demonstrated by these facets on the tibia and the talus along with retroversion of the tibial plateau due to the hyperflexion and pressure from the femoral condyles on the posterior aspect. This combination of features has been recorded in many East Asian and Indian cadaveric and skeletal collections as well as in Neanderthals; the latter was first noted by Charles in 1893 and by subsequent researchers in the early 20th century (Trinkaus 1975: 327). These facets are arguably formed from excessive contact of the talus and tibia, which only occurs in hyperdorsiflexion and not in regular locomotion; in fact, average-length ligaments prevent these bones from articulating in such a manner unless squatting is habitually practiced, thus lengthening the surrounding ligaments. Trinkaus' analysis of a number of previous studies found that medial facets are rare, but that lateral facets are common in all assemblages studied: the highest proportion was seen in a Japanese group (80.8%), known to be habitual squatters, but was still 38% in medieval Icelanders, for whom squatting was not a habitual posture. Lateral facets were observed in 50-68.2% of Neanderthals, depending on the group and including juveniles, although sample size was small (Trinkaus 1975: 339). As the facets are recorded in groups of non-habitual squatters, it is possible that they are the result of other activities that dorsiflex the ankle and therefore cannot be diagnostic of squatting alone. Other potential activities that dorsiflex the ankle are walking up an incline or a partial squat performed as part of other non-resting activities. A study of medieval Dutch populations – which, due to the flat landscape, removed inclined walking as a factor – showed higher rates of squatting facets in rural groups than urban, possibly indicating an active component to facet maintenance (Inskip *et al.* 2016).

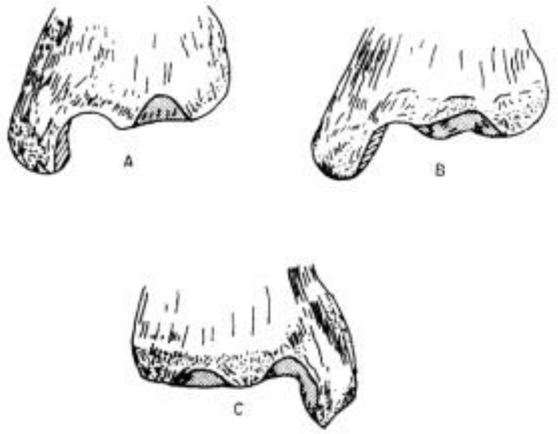


Figure 2.2.9 Illustration of medial **(A)**, lateral **(B)**, and combined **(C)** squatting facets on the distal tibia, as taken from Trinkaus (1975: 337), after Singh (1959).

2.3 Muscles and soft tissue

Muscle activity during motion can alter the process of bone shape formation, and other soft tissue structures may also have an effect on bone shape (see discussion below). Thus the structure of muscles and tendons surrounding the tibia and fibula is presented here with illustrations for guidance.

Skeletal muscles are formed of bundles of multinucleated fibres and are used to move bones by contraction and extension through the somatic and branchial motor nerves. These muscles (as opposed to cardiac muscle and smooth muscles) are paired: one to extend a joint and the other to flex. Within the body, muscles are grouped into compartments surrounded by fascia (Johnson *et al.* 1973; Netter 2006). Muscle does not attach directly to bone: tendons made of tough parallel collagen fibers connect the two and can modulate the muscle's reach, adding kinetic energy by acting as a spring (Hall 2012). Like bone and muscle, tendons can remodel in response to activity, although at a different rate than either. Muscles each have an origin and an insertion on adjacent bones, i.e. originating on the femur and inserting on the tibia to flex and extend the knee. An illustration of the muscles of the leg is shown in Figure 2.3.1, and a list of the muscles discussed in this section and their origins, insertion, and primary actions is featured in Table 2.3.4 at the end of this section.

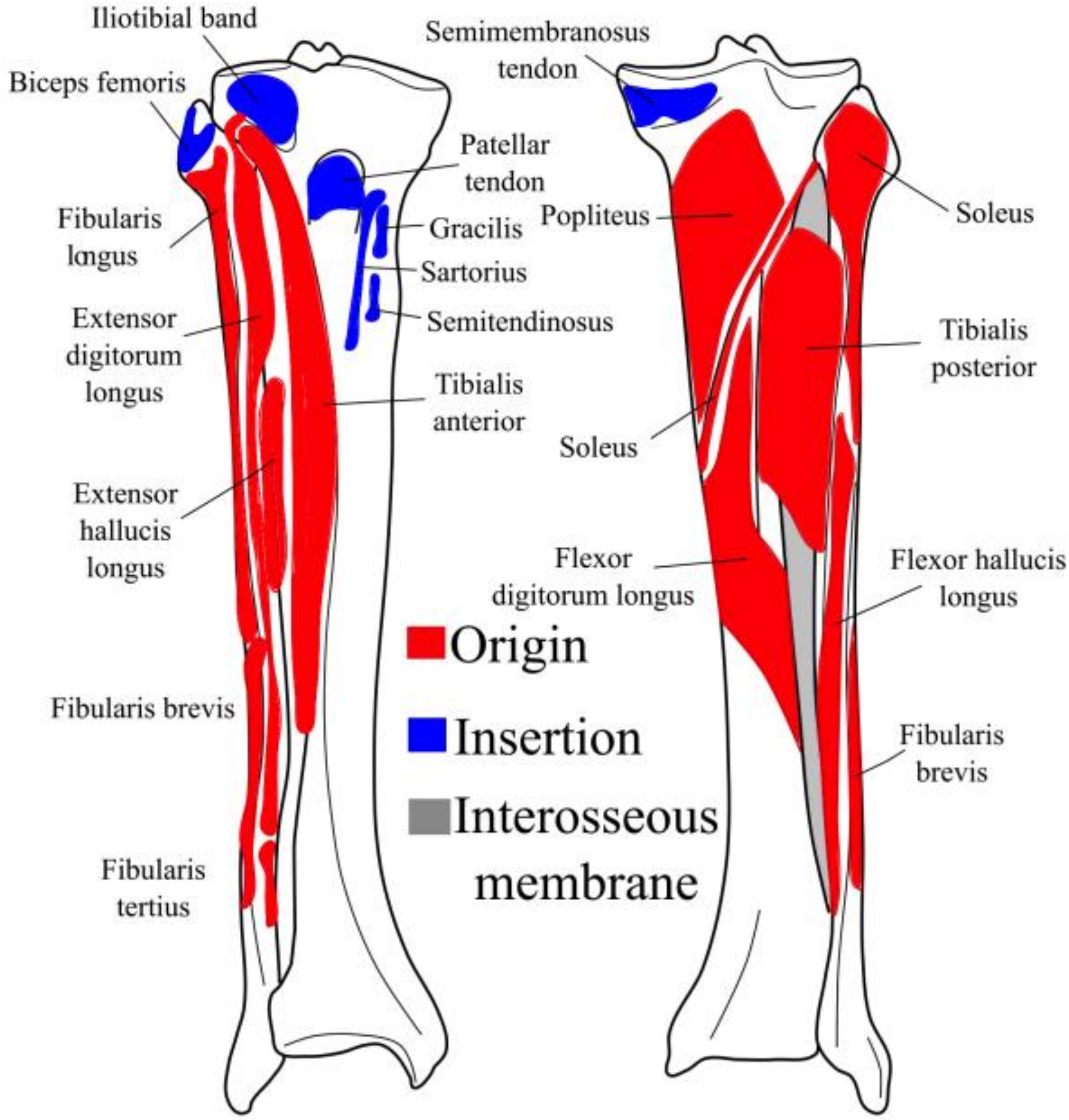


Figure 2.3.1 Illustration of the muscles inserting and originating at the tibia and fibula. An anterior view is shown at left and a posterior view is shown at right. S. Hackner 2016.

The leg has three muscle compartments, the lateral, anterior and posterior (see Figure 2.3.2). The muscles originating from the tibia largely control actions of the ankle and foot rather than the knee. The lateral, or everter, compartment contains the muscles that turn the foot outward and inward and control plantarflexion of the ankle. They include the *peroneus/fibularis longus* and *peroneus/fibularis brevis*. These both originate from the fibula and insert into the plantar surface of the foot (Netter 2006; Drake *et al*. 2010: 592). A diagram of the leg in cross-section with the muscle compartments highlighted is shown in Figure 2.3.2.

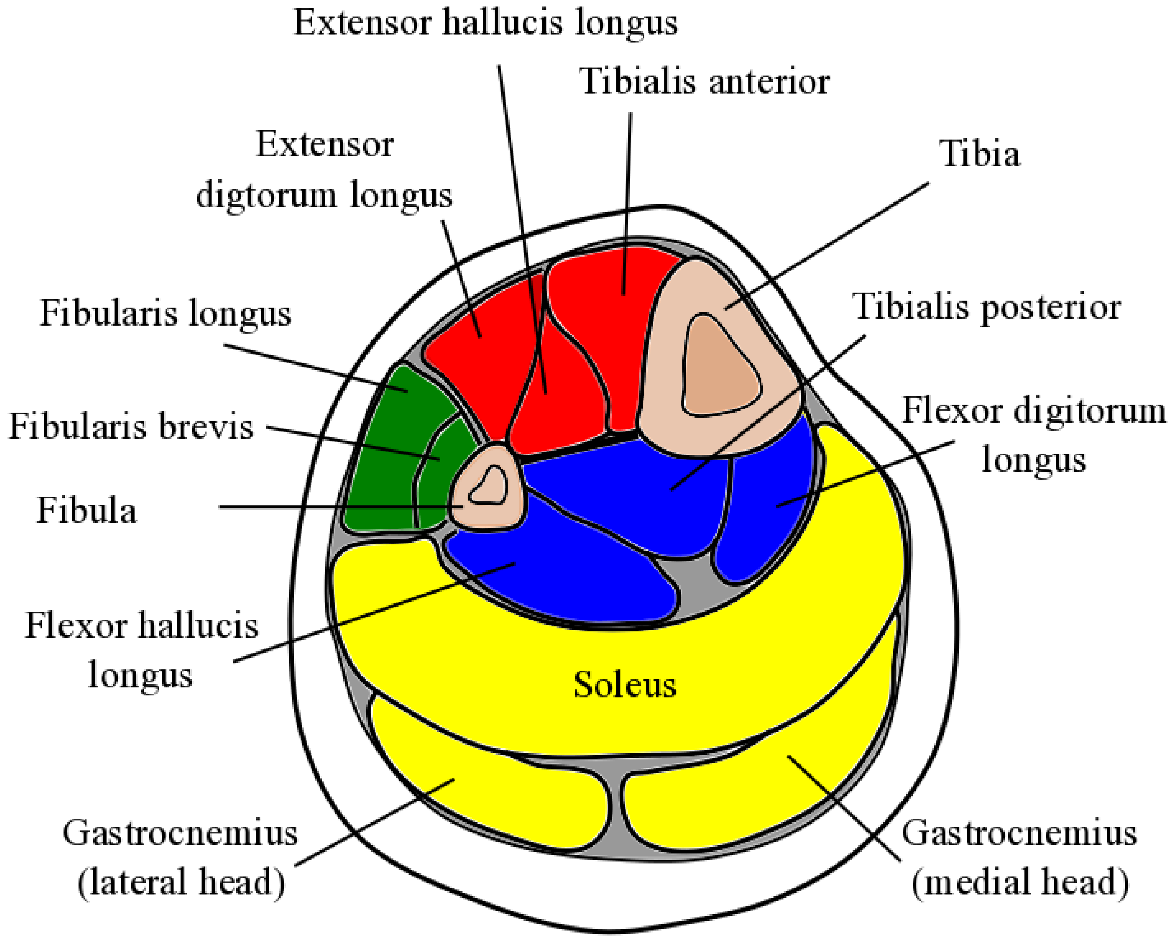


Figure 2.3.2 Illustration of the leg in cross-section at midshaft, showing the muscles and bones. Colours indicate muscle groups divided by fascia: anticlockwise from top are the anterior group, lateral group, posterior group, and deep group. S. Hackner 2016.

The anterior, or extensor, compartment contains the four muscles that control dorsiflexion of the ankle. *Tibialis anterior* (in older texts called *tibialis anticus*), which inverts the foot and holds the foot's longitudinal arch, originates from the lateral condyle and upper two-thirds of the tibia and inserts on the medial surface of the foot (Drake *et al*. 2010: 596; Gray

1901). *Extensor hallucis longus*, which dorsiflexes the hallux and inverts the foot, originates from the anterior fibula and inserts at the hallux. *Extensor digitorum longus*, which dorsiflexes and extends the four outer toes, originates from the lateral tibial condyle and the interosseous membrane (see below) and inserts at the dorsal surface of the four outer toes. *Peroneus/fibularis tertius*, which everts the foot, originates from the lower third of the anterior fibula and inserts into the dorsal surface of the fifth metatarsal (Netter 2006; Drake *et al.* 2010: 598).

The posterior compartment is comprised of a superficial group and a deep group. The most posterior of the superficial group is the *gastrocnemius*. Its two heads originate from the medial and lateral condyles of the femur, and distally it attaches to the Achilles (calcaneal) tendon, inserting at the calcaneus (Drake *et al.* 2010: 588). The *plantaris* is a small muscle lying between the *gastrocnemius* and the *soleus*; it originates from the lateral edge of the femoral linea aspera and is estimated to be absent in 7-10% of the human population (Spina 2007). The *soleus*, central to the analysis of platycnemia, sits deeper than the *gastrocnemius* and, as a multi-pennate muscle, has separate anterior and posterior aponeuroses (angled tendinous attachments) at the lateral condyle of the tibia and the head of the fibula respectively (Spina 2007: 158; Netter 2006). The fibre bundles arising from each aponeurosis join at the median septum, itself a third aponeurosis (Figure 2.3.3). Distally, it joins with the *gastrocnemius* to form the Achilles tendon. The *soleus* controls ankle plantar flexion and maintains stability when standing, making it important in studies of human bipedalism (Agur *et al.* 2003).

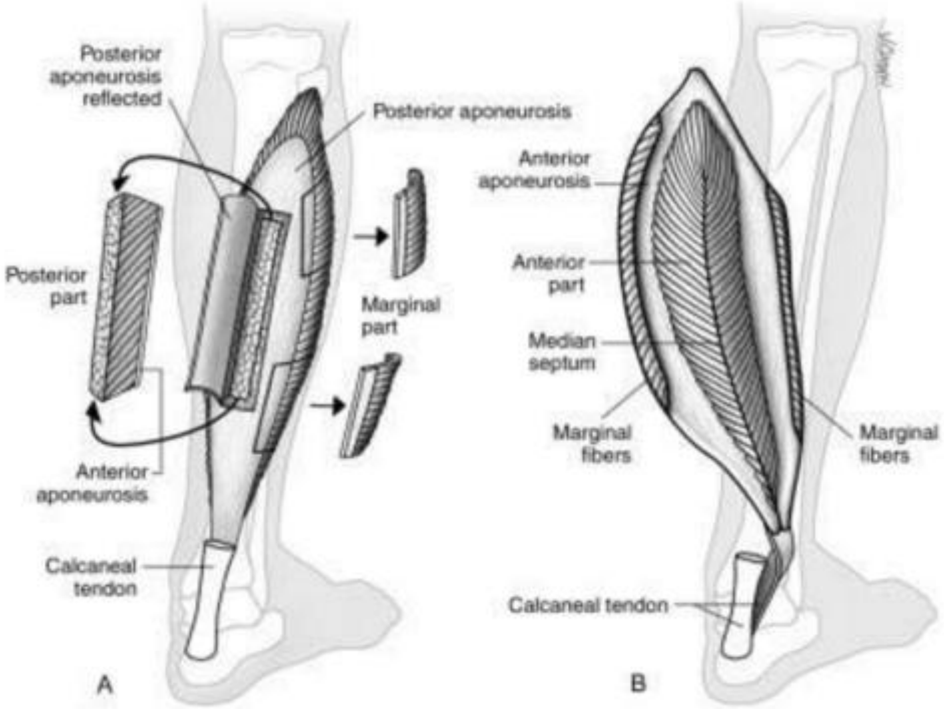


Figure 2.3.3 Diagram of the *soleus* muscle. **A**: Marginal and posterior soleus, postero-lateral view. **B**: Anterior and marginal *soleus,* anterior view (reflected and rotated). As taken from Agur *et al.* (2003: 286).

These two large muscles make up the *triceps surae*, commonly known as the calf. In some species the *triceps surae* is one muscle, as the *gastrocnemius* and *soleus* are fused; some other mammals have only a vestigial *soleus* or lack it entirely (Agur *et al.* 2003). Although its primary functions are flexion of the knee and plantarflexion of the foot, it is used in standing, running, jumping, and walking. Individually, the *soleus* steadies the leg on the foot and the *gastrocnemius* flexes the femur on the tibia; together, their action is to raise the calcaneus and therefore the rest of the body while keeping the toes and midfoot grounded in order to take a step, allowing the opposite leg to swing forward (Drake *et al.* 2010: 589).

The deep muscle group comprises the remaining four muscles of the leg, three of which serve to counteract the actions of muscles in the anterior group. The *flexor hallucis longus* is largest and sits lateral to the tibia (Drake *et al.* 2010: 591). It originates from the lower two-thirds of the posterior fibula and inserts into the hallux. It works against *extensor hallucis longus* by everting and plantarflexing the hallux. The *flexor digitorum longus* originates from the posterior distal two-thirds of the tibia and inserts on the plantar surface of the distal phalanges of the outer four toes; it plantarflexes the toes, which is important for gripping the ground. These two muscles enable walking by launching the leg onto the toes (Netter 2006; Drake *et al.* 2010: 591). *Tibialis posterior* is the deepest of all the calf muscles. It originates at the proximal end of the interosseous membrane and inserts into the base of the 2nd, 3rd, and 4th metatarsals. It holds up the medial longitudinal arch of the foot and inverts and plantarflexes the foot. The *popliteus* originates from the posterior side of the lateral condyle of the femur and inserts into the upper posterior surface of the tibia, just above the popliteal line (see below). It is the "key to the knee" as it rotates the tibia inward and the femur outward in order to flex the knee (Drake *et al.* 2010: 592). At midshaft, the muscles directly in contact with the tibial surface are the *tibialis anterior, tibialis posterior,* and *flexor digitorum longus* (see Figure 2.3.2), allowing for individual variation in muscle attachment sites and muscle belly positioning.

It is important to note that muscle as well as bone is subject to individual variation. Muscle insertions can overlap or change location; this can be due to injury or possibly contribute to it. Ekenman *et al.* (1995: 163) found that out of 36 cadaver legs, 2 had *soleus* muscles that did not actually attach to the tibia. They concluded that variations like this could contribute to tibial stress fractures. Rarely, there can be additional muscles such as the *soleus accessorius*, which extends from the deep surface of the *soleus* to the calcaneus and is easily inflamed by injury (Percy and Telep 1984: 449). It is due to early splitting of a single cell cluster from the *soleus* cluster in embryonic development. Other such muscles are the *peroneus quartus* and *flexor digitorum longus accessorius* (Christodoulou *et al.* 2004).

Muscle	Proximal attachment	Distal attachment	Primary action
Rectus femoris	anterior inferior iliac spine	patella	extension
Vastus lateralis	greater trochanter, lateral linea aspera	patella	extension
Vastus intermedius	anterior femur	patella	extension
Vastus medialis	medial linea aspera	patella	extension
Semitendinosus	medial ischial tuberosity	proximal medial tibia	flexion, medial rotation
Semimembranosus	lateral ischial tuberosity	proximal medial tibia	flexion, medial rotation
Biceps femoris: long head	ischial tuberosity	posterior lateral condyle of tibia, head of fibula	flexion, medial rotation
Biceps femoris:short head	lateral linea aspera	posterior lateral condyle of tibia, head of fibula	flexion, medial rotation
Sartorius	anterior superior iliac spine	proximal medial tibia	flexion, lateral rotation
Gracilis	anterior inferior pubic symphysis	proximal medial tibia	adduction of thigh, flexion of lower leg
Popliteus	lateral femoral condyle	posterior medial tibia	medial rotation, flexion
Gastrocnemius	posterior femoral condyles	calcaneal tuberosity via Achilles	flexion
Plantaris	distal posterior femur	calcaneal tuberosity	flexion
Tibialis anterior	upper 2/3 of lateral tibia	medial 1st cuneiform and metatarsal	dorsiflexion, extension
Extensor digitorum longus	lateral tibial condyle, head of fibula	2nd and 3rd phalanges four lesser toes	toe extension, dorsiflexion, eversion
Peroneus tertius	lower 1/3 of anterior fibula	dorsal surface of 5th metatarsal	dorsiflexion, eversion
Extensor hallucis longus	middle 2/3 of medial anterior fibula	dorsal surface of distal phalanx of hallux	dorsiflexion, inversion, hallux extension
Gastrocnemius	posterior femoral condyles	calcaneal tuberosity via Achilles	plantar flexion
Plantaris	distal posterior femur	calcaneal tuberosity via Achilles	assists with plantar flexion
Soleus	posterior proximal fibula and tibia	calcaneal tuberosity via Achilles	plantar flexion
Peroneus longus	head and upper 2/3 of lateral fibula	lateral surface of 1st cuneiform and metatarsal	plantar flexion, eversion
Peroneus brevis	distal 2/3 of lateral fibula	tubersoity of 5th metatarsal	plantar flexion, metatarsal eversion
Flexor digitorum longus	middle 1/3 of posterior tibia	distal phalanx of four lesser toes	plantar flexion, inversion, toe flexion
Flexor hallucis longus	middle 2/3 of posterior fibula	distal phalanx of hallux	plantar flexion, inversion, toe flexion
Tibialis posterior	posterior upper 2/3 tibia, fibula, IOM	cuboid, navicular, 2nd-5th metatarsals	plantar flexion, inversion

Table 2.3.4 Muscles controlling the knee and ankle joints, after Hall (2012).

2.4 Supplementary structures: bone features, periosteum, and fascia

In addition to bones and muscles, the leg, like other skeletal elements, incorporates a number of soft tissues and features that must be discussed for a complete understanding of function and shape. The bone features discussed are those that are not integral to joint function but are still important to tibial function and archaeological identification. The soft tissues here include any structure that is not muscle or the ligaments discussed in the previous sections on joints.

2.4.1 Bone features

The tibia has a large nutrient foramen used as the landmark for measurement of the tibial index. This foramen provides an entrance into the bone for the posterior tibial artery, which provides the blood supply during growth in utero and provides up to 80% of its interosseous blood supply in childhood (Kizilkanat *et al.* 2007: 87). Although all long bones have at least one nutrient foramen, that of the tibia is commonly the only one visible on neonatal remains. It is distally directed (it "flees the knee") and is towards the distal end of the proximal third or the proximal end of the middle third of the shaft, depending on the individual (Collipal *et al.* 2007; Kizilkanat *et al.* 2007), on the posterolateral side of the bone, generally in a straight vertical line distal to the soleal line. Rarely, it can appear on the medial side. It is possible but rare to have two foramina in this location, and there are no cases of an absent nutrient foramen in the clinical literature. The tibial nutrient foramen is a common site of longitudinal stress fractures, which can be accompanied by rupture of the associated artery; however, fractures at this site heal faster than fractures on the lower third of the shaft, possibly due to the increased blood supply from the artery (Kizilkanat *et al.* 2007).

The nutrient foramen is not located in a consistent place on the shaft, varying in location due to developing vascular systems in utero and early childhood growth (Dove *et al.* 2015). In one individual measured by the author, the difference between antimeres was 10 mm, leading to the question of whether it should ever be used as a landmark. Andermann (1976) and others in the late 20th century have suggested alternatives, but these rely on having complete bones and changing the standard measurement, making pre- and post-1976 results incomparable; for these reasons, researchers have continued to use the nutrient foramen despite its inconsistency (or without considering its variability). For example, the Buikstra and Ubelaker (1994) guidelines for measuring bones instruct the researcher to measure the anteroposterior and/or mediolateral diameters at midshaft of the femur, humerus, ulna, radius, and fibula, but to measure the diameters at the nutrient foramen on the tibia.

One feature of tibial bone morphology not commonly noted is the posterior pilaster. The feature is a rounded crest on the posterior side, originating at the same point as the soleal line but extending distally until about midshaft and rising up to 5 mm in height as a smooth, rounded, elongated protrusion (Figure 2.4.1). This feature is distinct from the soleal line and cannot be classified by the Hawkey and Merbs (1995) criteria for musculoskeletal markers. The nutrient foramen is often located on or lateral to this buttress. This is one reason many tibias studied, ranging from the Cro Magnon individuals examined by Broca to those currently under investigation, have rhomboid rather than triangular tibial midshaft cross-sections. The rhomboid shape is an example of one of Hrdlička's Type IV shafts, discussed further in Chapter 4.2, and thought to contribute to tibial flattening by McKown and Keith (1939), but is rarely considered in any other clinical or archaeological literature. It possibly arises from an action of the *soleus* or *tibialis posterior*; Lovejoy *et al.*'s (1976) review of relevant literature failed to find an adequate explanation. Vallois (1912; 1938) suggested that the posterior pilaster is a result of *tibialis posterior* hypertrophy, an explanation which Lovejoy *et al.* called "unlikely" (1976: 470). The posterior pilaster has been noted in some Sudanese assemblages in previous research (Hackner 2013).

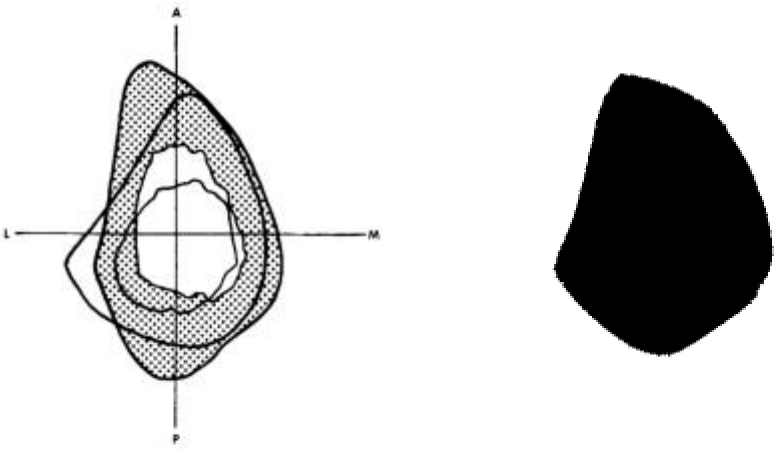


Figure 2.4.1 Left: diagram of the midshaft cross-sections of a eucnemic tibia (blank) over a platycnemic tibia (stippled) showing posterior pilaster, as taken from Lovejoy *et al.* (1976: 470). Right: a midshaft cross-section from a 3D scan from Jebel Moya (see Chapter 8) showing a tibia with a posterior pilaster (bottom of the image)

The soleal line (in some texts called the popliteal line) is the area of attachment for the *popliteus* insertion and *soleus* origin. It begins distal to the lateral condyle of the tibia and extends obliquely downwards towards medial (Bass 2004: 241). As the *soleus* is a large muscle used in some of the most basic human activities, it is often the site of osteophytes and can be scored for robusticity (Hawkey and Merbs 1995). Some better-preserved individuals in the study assemblages had muscle fibres still attached to the soleal line.

2.4.2 Membranes

The interosseous membrane (IOM), also called the tibiofibular ligament or the interosseous ligament, despite actually behaving more like a tendon, connects the lateral crest of the tibia to the medial crest of the fibula (Netter 2006). It is a thin, fibrous lamina with fibres running obliquely downward. The fibers of the IOM blend into the surface fibers of the periosteum, which then wrap around each bone and reconnect to the IOM fibers of the opposite side, enveloping the lower leg complex (Latta 1979: 11). Many of the leg muscles attach to or about it; important for this discussion is *tibialis anterior*, which may affect the sharpness of the interosseous crest. The membrane is broader and thicker at the proximal end than the distal end, and is incomplete at the upper and lower margins, allowing the anterior tibial vessels to pass through the patent gap at the proximal end and the anterior peroneal vessels at the distal end. Distally, it becomes the interosseous ligament, discussed above (Gray 1901: 282; Stevens 2006; Attarian *et al.* 1985). The IOM of the leg has not been as thoroughly-researched as that of the forearm, probably – like the fibula – due to its secondary role in weight-bearing (Latta 1979: 9). As the ligaments connecting the tibia and fibula only provide 20% of the leg's axial stiffness, the IOM's main role appears to be providing the bulk of axial stiffness, which enables proper function of the dorsiflexors and plantarflexors of the ankle (Latta 1979: 9). It has been noted that collagenous tissues organized into bundles can increase in size when stressed, which Latta argued can be extrapolated to the IOM as it experiences similar loading to the fibula. Biomechanically, the orientation of the IOM relative to the fibula applies simple, regular stress distributed evenly along the direction of the fibers (Latta 1979: 4). Like a tendon, the IOM is loaded uniaxially with little bending or rotation. In dry bone studies, a tibiofibular complex with a resected IOM showed more posterior displacement of the fibula, indicating that it has a secondary, tendon-like purpose in addition to load distribution (Latta 1979: 61). Thus far, no research has investigated the result of IOM loading on the prominence of its tibial attachment or on tibial shape.

The periosteum is a fibrous membrane that covers all bones except the patella in all places except where covered by articular cartilage (Dwek 2010); in the leg and lower arm, as mentioned above, the periosteum directly connects to the interosseous membrane, and covers the bone-adjacent parts of entheseal attachments. Periosteum comprises two layers: the outer densely fibrous layer consists of dense, irregular connective tissue made of Type I collagen and elastin (Waldron 2009: 20; Modric 2013), and can be subdivided in two again. The outermost layer is predominantly small, compact bundles of collagen fibers interspersed with elongated fibroblasts and is highly vascularized and enervated, while the deeper layer is much more elastic and cell-poor and contains the ends of tendinous attachments (Dwek 2010). The inner periosteal layer consists of mesenchymal progenitor cells that develop into fibroblasts and osteoblasts, which lie in contact with the cortical surface. The periosteum is 0.07-0.15 mm thick in growing individuals, but thins with age and thickens in inflammatory periosteal reactions. The osteogenic inner layer is thickest in fetuses and in later age becomes indistinguishable from the outer fibrous layer (Dwek

2010). It is attached through the bone to the endosteum – its equivalent in the medullary cavity – by Sharpey's fibers, which are especially abundant at the entheses (Modric 2013). The primary purpose of the periosteum in growing bone is the production of osteoblasts, resulting in appositional bone growth and bone repair in the event of fracture, sometimes acting as a hinge to hold disconnected fragments of bone in place; the balance of bone production and resorption trends towards positive on the periosteum (Waldron 2009: 19). Secondarily, the outer layer contains the periosteal arteries and veins, which contribute to the blood supply of muscle-adjacent bones, while the inner layer's vessels provide blood to cortical bone (Netter 2006).

The periosteum only has one reaction to stimulus, which is to form new bone (Ved and Haller 2002; Waldron 2009: 19; Weston 2011). Relevant to this study is medial tibial stress syndrome, commonly called shin splints, which is an exercise-induced inflammation of the anterior tibial periosteum; the tibial diaphysis is the most common site of injury in distance runners, with severity ranging from increased periosteal reaction to periosteal edema (Bergman *et al.* 2004), shown in Figure 2.4.2. The middle to distal tibia is subject to periosteal inflammation (sometimes referred to as periostitis) from repeated minor injuries, which can cause a periosteal reaction resulting in new bone formation. Towards the ankle, periosteal new bone is likely to be either an enthesophyte from tibiofibular movement or a reaction to varicose veins (Waldron 2009: 116). Periosteal new bone is often referred to as a stress marker, although Waldron (2009: 116) pointed out that it can be laid down in situations which are not stressful and is a part of normal bone growth.

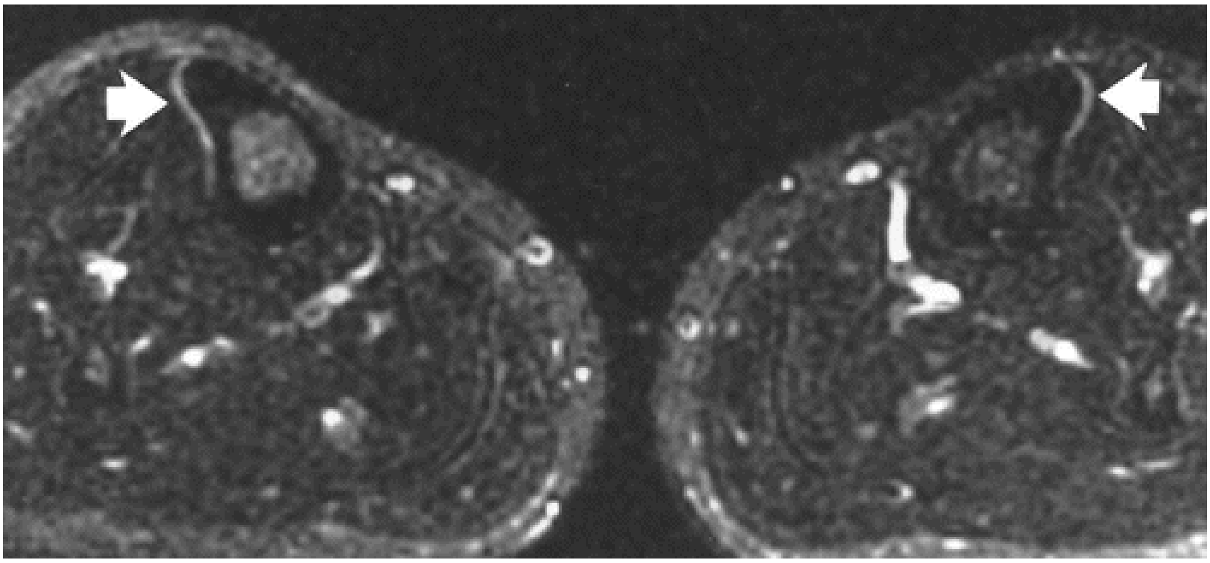


Figure 2.4.2 Bilateral tibial MRI with radionuclides, showing periosteal reaction (arrows) on the anterolateral border, as taken from Bergman *et al.* (2004). Note also the shape of the tibial shafts, shown here in an 18-year-old female.

The biomechanical properties of the periosteum in humans have not been thoroughly investigated. In a study of adult male rats, the femora and tibiae were subjected to postmortem loading either with periosteum intact or having the periosteum stripped (Yiannakopoulos *et al.* 2008). While differences in strength and stiffness were not significantly different between the groups, energy resorption and deflection were significantly higher in the bones with intact periosteum, and the stripped bones were more prone to failure and breakage (Yiannakopoulos *et al.* 2008). The authors did not state what properties were measured for strength and stiffness. Likewise, Kitaoka *et al.* (1998) found that goat ribs with periosteum could sustain 25.2% more deformation than those without the periosteum. Only recently has research investigated the effect of periosteal strain on tibial shape (Carpenter and Carter 2008), and all studies of periosteal biomechanics stripped away the muscles and tendons (Lanyon 1987; Kitaoka *et al.* 1998; Yiannakopoulos *et al.* 2008), which present a significant load. As the periosteum is the key zone of osteoblastic deposition, it deserves to be examined in concert with shaft shape formation and change. Carpenter and Carter's (2008) simulated mechanical model suggested that tensile periosteal strains perpendicular to the cortical surface can impede resorption or induce formation, working in combination with intracortical stresses to develop varying cross-sectional shapes. The periosteal response to pressure may take one of two forms: a direct osteoclastic response to small surface pressures or reduced blood flow due to pressures covering a greater area (Carpenter and Carter 2008: 231). The researchers argued for a combined concept of bone remodeling that takes into account both intracortical stresses due to tension, compression, and torsion (discussed below in section 2.5) and local periosteal stresses due to muscle activity, which can be as minimal as muscle presence or absence. The model indicates that bone cross-sectional size is determined by large-scale mechanical loads and that shape is determined by local periosteal pressure (Carpenter and Carter 2008: 238). This is of great importance to the types of tibial shaft shapes seen archaeologically (Chapter 4.1) and investigated in this study.

2.4.3 Fasciae

Fasciae are aponeurotic fibers found throughout the body enveloping softer organs and muscles to hold them in place. The superficial fascia is found directly beneath the skin, connecting the skin to underlying structures. Deep fasciae are thicker and inelastic, providing anchors for muscle and bone structures (Gray 1901: 296; Drake *et al.* 2010: 27). The leg contains a number of fasciae. The leg's deepest fascia is fused with the periosteum and attaches around the knee to the patella, tibial tuberosity, head of the fibula, and tibial condyles. Posteriorly, it covers the popliteal fossa. It is thicker in the proximal and anterior aspects of the leg where it attaches to *tibialis anterior* and *extensor digitorum longus* and is thinner posteriorly, where it attaches the calf muscles *gastrocnemius* and *soleus* (Netter 2006). Multiple intermuscular septa branch out on the lateral and posterior sides, separating and enclosing the lateral, posterior, and deep muscle groups; the superficial and deep muscle groups are separated by a broad transverse septum called the deep transverse fascia. These fasciae assist the muscles regulating pressure and tension on the muscles (Drake *et al.* 2010; Schleip and Klingler 2010). From a biomechanical perspective, much like the IOM, the fasciae appear to have a load-bearing function (Schleip and Klinger 2010). Ultrasound tests have also shown that fasciae are used for dynamic energy storage during oscillatory load-bearing movement such as running and hopping. While the associated muscles contract isometrically, the fasciae lengthen and shorten in what is called "the catapult mechanism" (Fukunaga *et al.* 2002; Schleip and Müller 2013: 3). Each soft tissue type discussed in this chapter – tendons, ligaments, aponeuroses, muscles, and fasciae – has a different composition and function and thus different biomechanical properties (illustrated in Figure 2.4.3), many of which are unexplored; it is unknown how much each contributes to total leg function and in what capacity, and specifically what role each plays in determining or changing tibial diaphyseal shape.

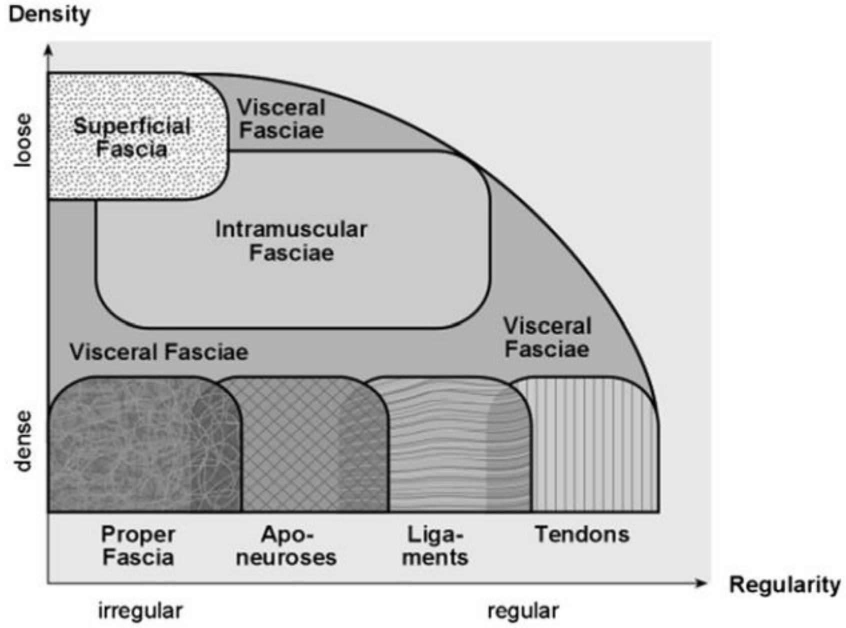


Figure 2.4.3 Chart illustrating the density and regularity of soft tissue elements, as taken from Schleip and Muller (2013: 2).

2.5 Biomechanics of the lower leg

This section defines biomechanics in general and biomechanics of the bones and muscles in particular. It addresses the methods current research in biomechanics uses to investigate differences between the bones of archaeological individuals and groups, applying data from sport science, in vivo animal studies, and cadaveric studies of humans to bioarchaeology.

Biomechanics investigates the forces acting within the body and on the body. It is the application of mechanical principles to living organisms, and in particular humans (Hall

2012: 2). There are many avenues of biomechanics research – sports and exercise science, kinesiology, aeronautics – and many applications, both to daily life and to unusual circumstances. For instance, research into how astronauts lose bone density in space is directly applicable to patients on bed rest or individuals suffering from osteoporosis (Leblanc and Schneider 1991; Leblanc and Schneider 1992). Occupational biomechanics attempts to decrease work-related injuries while sports biomechanics attempts to improve fitness and athletic endurance. Biomechanics research has improved prosthetic devices for amputees, investigated locomotor adaptations in ancient hominins, and tested loading forces in barefoot and shod runners.

Biomechanics attempts to break down motion into smaller, quantitative units. As humans are not perfectly linear and do not express forces as simple machines, human motion is difficult to examine as a whole: it is easier to focus on a single motion or lever (i.e. the knee in forward running) than the entire system (Hall 2012). Motion is broken down by directionality: rectilinear motion occurs in a straight line, curvilinear motion follows a curved line, while angular motion is rotation around an imaginary point or axis (Hall 2012: 31). General motion may consist of a combination of these. In forward track running, for example:

- The entire body moves forward rectilinearly
- The legs move rectilinearly at an angle to the body
- The upper arms move in a curvilinear fashion back and forth about an axis of rotation at the shoulder
- Body parts not actively engaged move in a figure-8 about their respective axes (Scurr *et al.* 2010; Zhou *et al.* 2012; Goldstein *et al.* 2012).

In addition, each body part may be broken down into its component segments (upper leg, lower leg, foot, toes) or examined by joint (lower back, hip, knee, ankle, tarsometatarsal, metatarsophalangeal), by bone (pelvis, femur, tibiofibular complex, tarsals, metatarsals, phalanges), or by muscle (numerous).

Bone biomechanics specifically examines the forces acting on bone, the body's hard tissue, and its subsequent ability to withstand mechanical loads in various activities. Bone must maintain a balance between stiffness and compressive and tensile strength. Compressive stress is stress that works to shorten an object, and tensile stress works to lengthen an object. Another type, shear stress, acts parallel to the bone surface. Stiffness is required to support the body and organs as scaffolding and is provided by bone's mineral content, constituting 60-70% of dry bone weight (Hall 2012: 88). Bone's ability to resist pressure (compressive strength) is based on its mineral structure as well; bone can be compressed in a number of ways, illustrated in Figure 2.5.1. Tensile strength, provided by bone's collagen content, alleviates the stiffness and allows the bone to be somewhat flexible. These features are not static, but an imbalance in minerals and collagen is the cause of pathology such as rickets, which is a deficiency in mineralization, or osteogenesis imperfecta, a deficiency of collagen (Waldron 2009). The mineral-collagen ratio in bones can withstand the compression and tension of several activities, with strength increasing each time the activity is performed in succession. (Bone remodeling will be discussed further in section 2.6.) It should be noted that compression and tension rarely act singularly on the bone: most stresses are complex, making mathematical models assessing only unidirectional stress imprecise (Ruff 2008: 185). Additionally, bone biomechanics is informed by beam theory, treating the bone as if it were a beam used in construction. The midpoint of a beam bears the most stress and thus in a malleable system is the most liable to undergo change and remodeling. Almost all studies of bone biomechanics use the midpoint, often in addition to other points on the shaft, because of its propensity to experience the maximum stress and has been correlated with terrestrial mobility, discussed further in Chapter 4 (Stock 2006; Shaw and Stock 2011; Macintosh *et al.* 2014). The reasons for using only the midpoint in this study are discussed in Chapter 7.2.

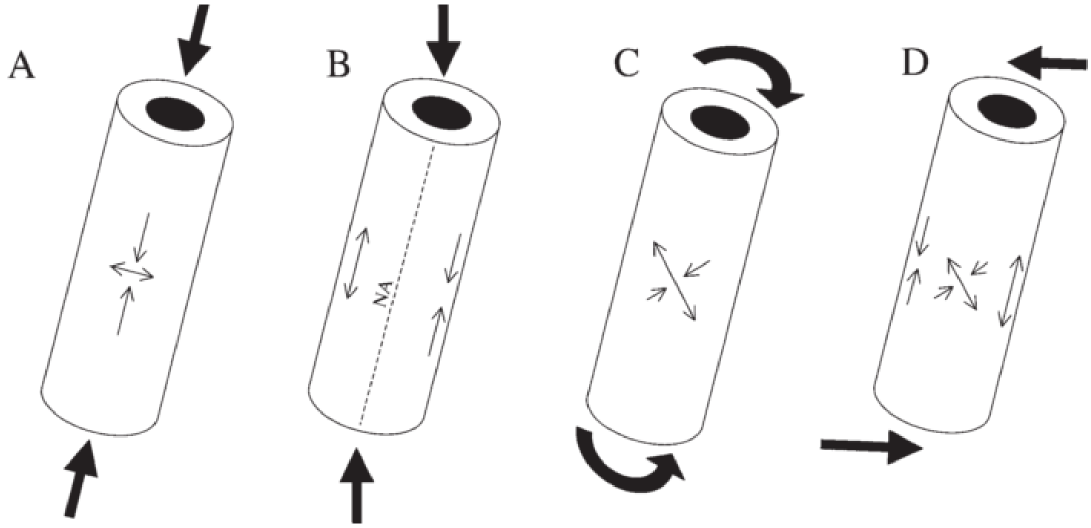


Figure 2.5.1 Diagram of cross-sectional schematic views of force and strain in compression (A), bending (B), twisting (C), and shear (D). As taken from Pearson and Lieberman (2004: 66).

Bone is to some extent elastic. The stress-strain coefficient at which bone experiences elasticity – that is, it returns to its original shape – is called Young's modulus (Pearson and Lieberman 2004: 68). When the force of a motion is too great, the stress exceeds Young's modulus; the bone can become deformed plastically, and the result is a fracture. Fractures can be linked to the direction of excess stress: spiral or oblique fractures are caused by excessive bending or torsion around a bending moment, a particular point on the side of the bone that experiences the most force. Young's modulus can change in response to continuous stress to the point of fatigue or if the stress is cyclical in nature, decreasing the strain per second (Pearson and Lieberman 2004: 67). Another type of fracture, the stress fracture, is caused by low-magnitude forces sustained over a long time. A stress fracture may occur if the magnitude or frequency of an activity is increased (Hall 2012:103).

Biomechanics investigates the physical forces necessary to cause fracture and what can be done to prevent it by studying bone loading both in vivo and in dissected limbs. One difficulty of in vivo studies has been attaching strain gauges to living humans and resuming normal activity (Burr *et al.* 1996), resulting in low participant numbers. Two adult males demonstrated different speeds of walking and running in Burr's study to examine principal strains at the tibial midshaft as follows in Table 2.5.2:

Activity	Compressive strain	Tensile strain	Shear
Uphill walking	-630	+440	+1065
Sprinting	-968	+646	+1583
Zig-zag run uphill	-1126	+743	+1966

Table 2.5.2 Strain rates measured in microstrain for various activities performed five times each by two participants, after Burr *et al.* (1996: 406).

Strain was approximately two to four times greater during running than walking, no matter the slope. The study also demonstrated the remarkable change in strain between parts of the gait and the rapid changes in strain to which the bone and surrounding muscles must adapt. However, results from this study may not be applicable worldwide as the study involved only two adult male participants: strain and shear rates may differ based upon bone mineral density, which varies by age, sex, hormone levels, and history of activity, as will be discussed in Section 2.6 below.

One scale up from bone minerals is bone microstructure. Long bones are composed of two subtypes of bone: trabecular (or cancellous) bone and cortical bone (see Figure 2.5.3). The external "shell" of the bone is cortical or compact bone, including the periosteum, and provides much of calcium content and dense rigid support. The main unit of cortical bone is the osteon or Haversian system. Osteons are around .2 mm in diameter and arranged in concentric rings (or lamellae) of compact bone around a central Haversian canal running parallel longitudinally to the main axis of the bone (Currey 2002; Netter 2006); Currey described osteons as resembling leeks (1984: 28).

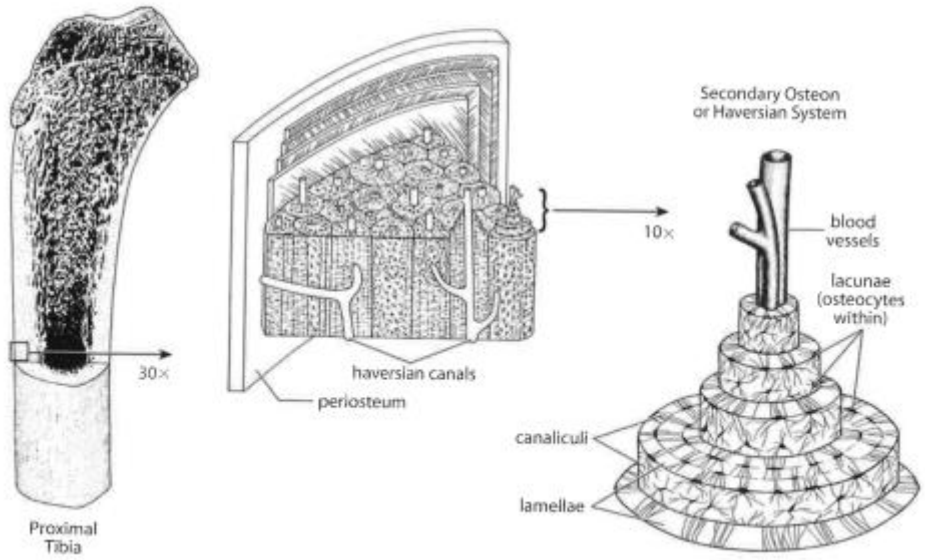


Figure 2.5.3 Diagram of bone at three decreasing levels of magnification: transversely sectioned bone displaying cortical and trabecular bone (left), periosteum and many Haversian canals (middle), and a single Haversian system (right). As taken from White *et al.* (2012: 34).

Trabecular or cancellous bone makes up the interior and is much less dense (Netter 2006). Trabecular bone is primarily found in the proximal and distal ends of long bones, become even less dense towards the middle. The trabeculae, or individual struts of bone making up this complex, are thought to be aligned in the main directions of mechanical stress (Wolff 1892; Pearson and Lieberman 2004). It is highly vascularized, and the vascular inlets can be seen on the external surface of the bone.

The key theory explaining bone microstructural growth in response to activity is Wolff's Law, theorized by Julius Wolff in 1892. The law stated that healthy bone adapts to mechanical loads in a mathematically-predictable manner: bone is deposited and resorbed to achieve an optimum balance between strength and weight, trabeculae line up in the direction of principal stress, and that these both occur through self-regulating mechanisms (Wolff 1892; Pearson and Lieberman 2004: 64). However, Pearson and Lieberman pointed out that it is "neither a law, nor completely true" (2004: 65), noting that the law is based on a series of both biological and mechanical misconceptions, the foremost of which is that bone is a homogeneous and solid structure (Cowin 2001). They, along with Ruff *et al.*

(2006) favor dropping the term entirely and instead asking four related questions regarding how bones perceive and translate forces and what factors modulate these responses, as follows:

> “1) What are the mechanical problems that confront bones? 2) How do bones perceive forces? 3) How do applied loads induce osteogenic response by various cell types in different regions? 4) What factors modulate these responses to generate variations in relationships between structure and function?” (Pearson and Lieberman 2004: 65)

The basic idea of Wolff’s Law has been stripped of its mathematical components and adapted to describe the concept of bone functional adaptation, shown in Figure 2.5.4. This modern interpretation relies on strain (deformation) rather than stress and places bone functional adaptation into a feedback loop with a central zone of equilibrium above which bone is deposited and below which bone is resorbed (Ruff *et al.* 2006: 485). Critiques of this point out that while mechanical loading influences the development of form in growing bone, there is no direct evidence of functional adaptation in mature, non-pathological bone. Additionally, studies in a number of non-human species have shown a consistent lack of correlations between strain patterns and cross-sectional geometry (Lieberman *et al.* 2004: 169), indicating a more complicated relationship than predicted by the original stipulations of Wolff’s Law or its modern equivalent, henceforth called bone functional adaptation. The processes by which bone is shaped and factors affecting this process are discussed in the next section.

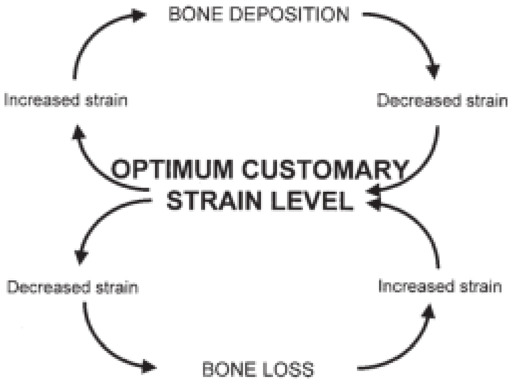


Figure 2.5.4 Simplified diagram of the bone functional adaptation feedback loop, as taken from Ruff *et al.* (2006: 485).

2.6 Bone growth in response to activity

Bone growth in response to activity is central to discerning archaeological groups based on bone shape. This section explores how activity induces bone growth biomechanically using examples from clinical studies, with discussion of how bone growth is affected by various intrinsic and extrinsic factors. Long bones grow and develop by a process called *remodeling*. It involves the cells osteoblasts, osteoclasts, and osteocytes (Currey 1984; Currey 2002). Osteoblasts are bone-building cells derived from stromal cells. They are related to osteocytes, which facilitate communication within the bone matrix (Mundy 1999: 30; Currey 2002). Osteoclasts are responsible for the resorption of bone and are more complex on a cellular level than the other two types. They frequently have ten or more nuclei and, in a pathological state, can have up to one hundred (Mundy 1999: 12). Osteoblasts are most active in relation to osteoclasts during growth throughout childhood, particularly during the periods of maximum growth velocity (commonly known as growth spurts) in early childhood and adolescence. However, research has shown that the type of bone and amount of bone that is developed during the initial modeling phase differs between individuals. Much of this differentiation is based on the age at which growth occurs, biological sex, and the activities individuals or groups perform, with increased loading during youth resulting in denser, thicker bones (Haapasalo *et al.* 1998; Stock and Pinhasi 2011; Hall 2012; Macintosh *et al.* 2014), shown in Figure 2.6.1.

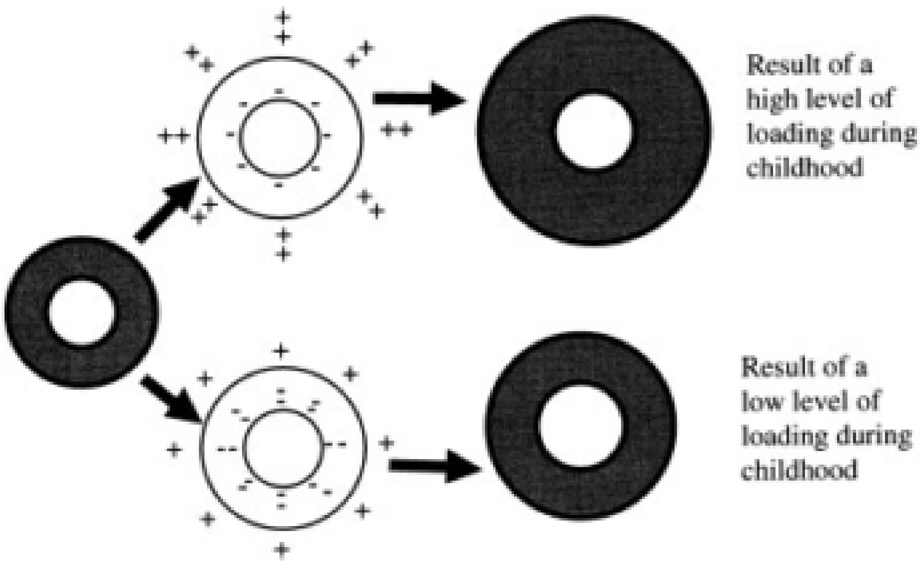


Figure 2.6.1 Illustration of bone growth in response to high and low levels of loading in childhood, as taken from Pearson and Lieberman (2004: 76)

One of the primary research questions that evolved from bone functional adaptation is why mechanical forces cause bone to increase in density and diameter in the particular ways researchers have observed. Adding bone mass in the direction of compressive forces – that is, by increasing cross-sectional area – the force is thus spread over a larger total area, minimising the compressive force experienced by one particular unit of bone. Additionally, by increasing the amount of bone further from the longitudinal axis, the bone becomes more resistant to bending and torsional stresses by augmenting second moments of area (Pearson and Lieberman 2004: 73). The particular mechanisms for translating mechanical force into chemical signals to induce remodeling are still unknown (Lanyon 1987: 1093). Note that bone growth discussed in this section is primarily measured in bone mineral density, bone mineral content, or cortical thickness rather than shape outline, as will be discussed later in Chapter 4.

2.6.1 Form and function: differences in bone remodeling by age and sex

Bones remodel in different ways and at different rates depending on age and sex. This section covers many of those differences, with a focus on what can be learned from clinical trials as well as the limitations and biases in those trials.

Age

Bone is uniquely responsive to the effects of exercise before the end of puberty. Numerous animal studies, which involve comparing animals running on treadmills to a sedentary control group, have shown that growing bone has a much greater capacity to add new bone to the skeleton than stable adult bone (Khan *et al.* 2000). There is a clear and simple reason for this: growing bones experience continuous osteoblast and osteoclast activity in the bone modeling phase. In response to exercise stress, more bone will be laid down by an activity that continually occurs anyway in this time period, and it is not an excessive metabolic strain to continue this process. In adults, bone is not modeled but remodeled; this process is episodic and only replaces up to 5% of compact bone and 25% of trabecular bone per year (Currey 2002), although that is dependent on age and sex (Frost 1969; Frost 1997). It also does not affect the gross shape of the bone, but rather occurs on a microscopic level as osteons remodel themselves and increase in number, a process termed Haversian remodeling (Scheuer and Black 2004: 45). Haversian remodeling refers specifically to the development of osteons, as opposed to the original modeling that causes an increase in mass on the periosteum and endosteal medullary canal (see Figure 2.6.2). In Haversian remodeling, the bone surrounding the blood vessel at the centre of an osteon is eroded and replaced (Currey 1984: 29). Nearly half of adult bone mass is gained during puberty, and bone modeling mostly ceases around maturation, at which point 95-99% of peak bone mass has been gained (Haapasalo *et al.* 1998: 311). Terms to be aware of in studies of bone remodeling are bone mass, bone mineral content (BMC) and bone mineral density (BMD), which is BMC adjusted for area (Deng *et al.* 2002: 359). Arguably, only BMC should be used in studies of growth as density should not be expected to change appreciably (Heaney 2003: 350), but studies still continue to report this metric.

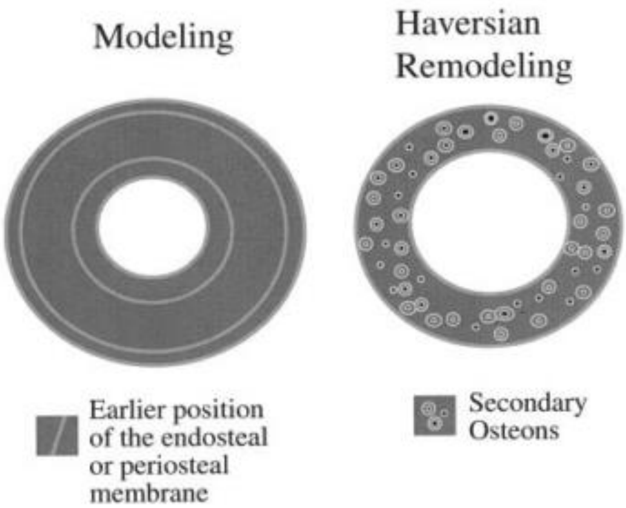


Figure 2.6.2 Illustration of Haversian remodeling vs initial modeling, as taken from Pearson and Lieberman (2004: 72).

Studies have been conducted both on children performing general weight-bearing activity and on children involved in a singular serious competitive sport. General weight-bearing activity may be a more accurate representation of how bone modeling occurs as it reduces the selection bias in studying youths who chose to participate in sport. It is possible that those individuals involved in sport chose it because of larger overall size or particular body proportions (Bradney *et al.* 1998: 1815). One longitudinal study of the former type found that after 12 months at maximum BMC velocity (the time at which BMC was found to increase the most rapidly, generally around 14.1 years), boys in the top quartile for general physical activity had 9% greater total BMC than those in the lowest quartile, while for girls the difference was 14% (Khan *et al.* 2000: 153). Another study found consistent positive associations between increase in BMD and total hours spent practicing weight-bearing sports only for boys aged 5-14 years; results were not significant for post-pubertal adolescents (Bradney *et al.* 1998: 1819).

A study of 45 ten-year-old female gymnasts found a 30-85% increase in total body BMD than controls after one year (Haapasalo *et al.* 1998); another smaller study found similar results with younger gymnasts (Khan *et al.* 2000). Both found increased BMD not only in the femur and lumbar spine but also in the radius (for which BMC was 51% higher than in non-gymnasts), indicating that the increase is, in fact, an effect of exercise as the arms are weight-bearing in gymnastics (Khan *et al.* 2000: 154). However, researchers disagree on the level of maturation necessary to rapidly increase BMD through exercise as some studies of gymnasts showed no increase in BMD until the mid-teens despite their practicing gymnastics since childhood.

To find a more accurate age association, Haapasalo *et al.* (1998) examined 91 young female tennis players aged 7 to 17 with the hypothesis that it is possible to determine the age of maximum BMD increase by examining their dominant (playing) arm. Tennis is an ideal sport for this as mechanical loading is unilateral rather than bilateral, as in gymnastics. The authors noticed a significant divergence in BMD between the dominant arm of players and controls at Tanner stage III (mean 12-12.6 years),[1] which corresponds to the adolescent growth spurt before menarche; this is also the only time when "bone is added in substantial amounts to the inner and outer sides of the bone cortex by endosteal and periosteal apposition" (Haapasalo *et al.* 1998: 316). The tennis players' BMD increased by 9% in the dominant proximal humerus, 10% in the humeral shaft, and 7% in the distal radius over the nondominant arm; non-playing controls experienced 2% or less increase in BMD. At Tanner stage IV (mean 13.2-13.5 years), the players' dominant arm BMD increased by 14%, 16%, and 12% respectively, and at Tanner stage V (mean 15.5 years) these increased by 12%, 15%, and 11%, showing a slight decline from the previous stage. The control group experienced almost no increase during these periods, shown in Figure 2.6.3. BMD at the lumbar spine was also assessed, but a difference was only found between players and controls at Tanner stage IV. No difference between the groups at any stage was found in the nondominant radius (Haapasalo *et al.* 1998: 317). This clearly shows that the effect of unilateral mechanical loading in athletics during growth most strongly affects individual females around age 13 (Tanner stage IV).

---

[1] The Tanner scale defines stages of adolescent growth and pubertal development as a more biologically-accurate rendition of growth than age in years. See Marshall and Tanner (1969) for full descriptions.

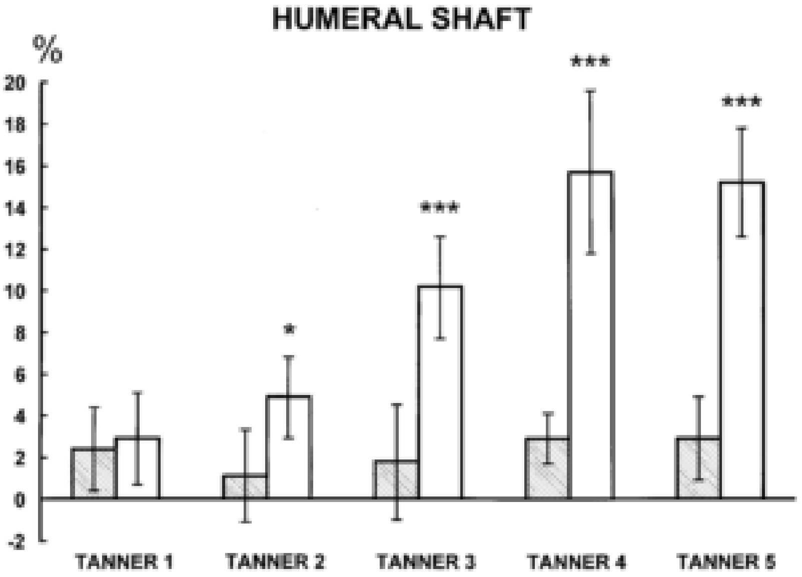


Figure 2.6.3 Graph of side-to-side BMD difference between the dominant arm and the nondominant arm between tennis players (open bars) and controls (shaded bars), as taken from Haapasalo *et al.* (1998: 315).

Assessing the dominance of one side using bone shape or density is difficult to determine. Directional asymmetry, defined as consistent difference between morphological structures favoring one element, is present in the upper limb bones of humans to a much greater extent than in any other animal (Ruff and Jones 1981), but asymmetry in the lower limb is less distinct. Although some authors (Wanner *et al.* 2007) have found significant asymmetry in the tibia in archaeological groups, most have not. In a study of asymmetry of the subperiosteal tibial area, Ruff and Jones (1981) found differences of less than 2% between sides; the left side was consistently larger than the right, corresponding with left-biased measurements of fetal leg side differences noticeable at four months' gestation in older publications (Schultz 1923; Schultz 1926). Other researchers (McCartney and Hepper 1999) have found differences in upper limb preference (handedness) and asymmetry, indicating that there may be an underlying genetic factor that determines both handedness and limb size even before activity has a direct effect postnatally. Another possible cause, Previc's neurodevelopmental hypothesis, asserts that the asymmetric position of the fetus in higher primates encourages left-sided vestibular growth and predisposes most individuals to use the left side for balance and the right side for motor control, resulting in right-handedness, eyedness, earedness, and footedness for motor tasks (Gabbard and Hart 1996), although use for postural strength does not fully explain the slight enlargement of the left lower limb bones. Ball-kicking and kneeling tasks prove most test subjects, at least in European contexts, to be right-foot dominant (Dittmar 2002). It should be noted, though, that the preferred hand and foot are not always utilised for the entire length of an activity. Most human motions – running, swimming, walking – involve equal bilateral motion, and a repetitive task beginning with use of the dominant limb will tire it, and the individual may switch to the non-dominant side, though it remains to be studied the extent of the non-dominant side's contribution to the overall activity. Further, a ball-kicking task may demonstrate the dominant foot, but a fast-paced football game will require adept kicking with both feet (Bailey 2014), causing similar biomechanical stresses to both the dominant and non-dominant leg. Directional asymmetry has been investigated bioarchaeologically and will be discussed briefly in Chapter 3.5.

Note that all of the above studies examined bone mineral density or bone mineral content rather than shape. Little work has been done on juvenile tibial shape in cross-section, and even Scheuer and Black's guide to juvenile bone identification describes the perinatal shaft as "triangular" (2004: 359), and that tibial torsion is visible on the anterior crest even before walking, although the angle of torsion changes from medial to lateral over the course of childhood. Towards puberty, the borders of the shaft become sharper (2004: 362), probably as a result of increased muscle mass and the effect of the interosseous membrane. CT scans of the tibiae of juvenile laboratory animals show the tibia to have a sharp anterior crest and rounded medial and lateral posterior edges (Lanyon *et al.* 1975; Moustafa *et al.* 2009; Vickerton *et al.* 2014).

There are significantly fewer studies of bone formation or remodeling in young and middle adults than of juveniles, and there are also few studies on child growth after those individuals have ceased physical activity. Those that exist are complementary to the studies on youths: in every study, the difference in BMD increase between athletes and controls was much smaller than in children. A study of male army recruits completing basic training found an increase in BMD of up to 11.1% (Margulies *et al.* 1986: 1091), but classified all 18-21 year-olds as adults when many of them could be in Tanner stage V, at which point many bones still have not completely fused. A study of Japanese males age 23-31 assigned to intensive exercise and control groups found an initial decrease in urinary deoxypyridinoline, indicating a slowing of bone resorption, and then stabilization among the exercise group (Fujimura *et al.* 1997). No significant changes in BMD were noted at any site. The exercise group also had increased serum levels of osteocalcin and other proteins indicative of bone formation (Fujimura *et al.* 1997: 658). However, the study only continued for four months, which may not be enough time for adults to form new bone. Contrarily, a study of American males age 50-70 divided into similar groups did show an increase in BMD at the femoral neck and lumbar spine at 2±0.9% over the control group as well as an increase in serum osteocalcin after 16 weeks (Menkes *et al.* 1993: 2482). There could be a number of reasons for the differences between the two studies: the types of activity could have differed, hormonal levels could be different among different age groups or ethnicities, or perhaps older males have less dense bone to begin with and therefore build it up differently; explicit in the first study but not the second was the ethnicity of the participants.

Advanced age leads to a decrease in BMD and overall bone mass for a number of reasons. As discussed above, bone ceases to model at maturation and begins to remodel; effectively, osteoclasts work faster than osteoblasts. Osteoporosis begins to occur when significantly more bone is resorbed than is formed – the places from which most cortical bone is resorbed are the long axes of bones where compressive and tensile stress is highest (Stini 1990: 167). As these areas are resorbed without being remodeled, the bone eventually loses its compressive and tensile strength and may fracture (Hall 2012: 100). In addition, trabecular bone once resorbed is *not* remodeled, weakening the interior of the bone. Osteoporosis is divided into two types: type I primarily affects postmenopausal women and trabecular bone before cortical bone, and type II is associated with senescence in general and appears to be an extended period of cortical bone loss. Type II affects men and women equally (Stini 1990: 172). Osteoporotic hip fractures affect both men and women, and in both sexes can be delayed or prevented by physical activity (Kujala *et al.* 2000: 705). The studies cited above maintain that the more bone built up during adolescence, the longer it takes to break down at senescence (Lazenby 1990b). Not only does physical activity affect bone shape and density, but also the rate of decline later in life.

In addition to becoming less dense, bone also loses strength as it ages. When bone is resorbed, it occurs from the medullary cavity outwards. A 70-year-old with the same BMD as a 20-year-old is prone to more fractures, due to lowered stability of the bones and muscles leading to a higher rate of falls (Sterling *et al.* 2001: 116). This is due not only to density but to decreased bone volume (both cortical and trabecular), which lowers the number of load cycles bone can endure before it breaks. Old bone has a higher mineral content than young bone, making it more brittle (Rosen *et al.* 1999: 307). It can be inferred from this that as older individuals are less able to build up bone, changes to the shape of the bone occur early in life, probably around late adolescence or early adulthood. However, there is evidence for continued periosteal apposition (CPA) at some skeletal locations such as the brow ridge and craniofacial area (Lazenby 1990a; Lazenby 1990b), and has been observed to a greater extent in males than females. In the postcranial skeleton, CPA has been observed as an intermittent event decreasing in frequency with advanced age (Lazenby 1990: 457); one reviewed study found increased periosteal bone in the metacarpals of older females, arguably in response to endosteal bone loss. This bone growth would not be the result of mechanical loading, complicating previously-stated hypotheses of periosteal modeling and remodeling. Another proposal for CPA was fracture repair, which Lazenby argued would not explain the sex-specific growth, particularly with regard to females losing bone mass post-menopause. It is unclear which bones and, in fact, which bone surfaces experience CPA (Lazenby 1990b). Additionally, shape change as a result of CPA has not been examined. The low number of accurately-aged individuals in the present study make arguments for CPA useful for considering functional adaptation with advanced age but not strictly relatable (see Chapter 8).

Sex

It is easy to misattribute cultural differences to sex differences, as happened with Osgood-Schlatter Disease, discussed above in section 2.1. However, there are some important hormonal differences that affect bone development unequally between the sexes. Sexual dimorphism in humans is not as great as in other animals (Larsen 2003) and there tends to be significant overlap, but generally, males are larger and more robust than females; the amount of dimorphism is heavily dependent on population genetics and environment. Some of the study populations showed a high rate of sexual dimorphism both in tibial length, diameter, robusticity, and shape, which will be discussed in Chapter 9.

One reason studies of older juveniles divide by sex is because females and males develop at different rates during puberty under the influence of different hormones. As discussed above, girls began to achieve significantly more BMD from exercise during the pubertal growth spurt (Haapasalo *et al.* 1998: 315). Similarly, Devlin *et al.* (2010: 609) found that young women in the highest tertile of physical activity gained significant bending strength in the femoral neck in the first year after menarche, when proteins derived from estrogen are highest. Estrogen derivatives prompt growth of the female reproductive organs and ovulation as well as driving the development of secondary sex characteristics which form the basis for the Tanner scale used in the study by Haapasalo *et al.* (1998). Numerous studies suggested that estradiol may influence bone strength as well as a growth, which would indicate that individuals with higher pubertal levels of estradiol are able to build stronger bone in response to mechanical loading (Devlin *et al.* 2010: 610). Individuals with a lack of these proteins will experience delayed or absent epiphyseal union and experience premature osteoporosis. The exact nature of the relationship between bone growth and estrogen is unknown, as estrogen increases at the same time bone experiences maximum growth velocity, but co-occurrence should not be confused with causation (Rosen *et al* 1999: 119).

On the other hand, estrogen works to model bone in males as well, both during puberty and in later life; it similarly declines at senescence, causing osteoporosis albeit at a slower rate in males (Rosen *et al* 1999: 119). Testosterone works in addition to estrogen, and males with suppressed testosterone had reduced levels of serum osteocalcin (Arisaka *et al.* 1995; Prakasam *et al.* 1999). It is possible one of the reasons men do not get Type I (or post-menopausal) osteoporosis is the protection offered by building bone through two hormone channels, so that when estrogen is depleted they can rely on the additional effect of testosterone (Frisco 2016). Various studies reported report that while differences in BMD between sexes is equivalent relative to body size, females achieve greater BMC and BMD in early puberty only to be surpassed by males in late adolescence (Boot *et al.* 1997; Mølgaard *et al.* 1998; Arabi *et al.* 2004; Yilmaz *et al.* 2005), who additionally retain it longer in adulthood; additionally, there are differences in locations of maximum density (Kujala *et al.* 2000).

In studies of adolescent athletes, emphasis on growth and development differs for males and females. One big difference is menarche. It provides a convenient sectioning point for studies of growth during female pubescence despite occurring at different ages and developmental stages (Devlin *et al.* 2010). Studies of pubescent males do not have so neat a marker. Of additional interest is the contradictory information on the threshold of activity in females: numerous studies list the benefit of activity for females as increased BMD can prevent or delay osteoporosis, but at some point exercise actually prevents epiphyseal union and delays menarche. A longitudinal study of 22 gymnasts selected for elite training grew at slower rates, achieved shorter heights than predicted, experienced oligomenorrhea or amenorrhea and delayed menarche, and – most interestingly – experienced growth spurts when they reduced training because of injury rather than at the average developmental stage compared to an age-matched control group (Lindholm *et al.* 1994; Lindholm *et al.* 1995). There is potential for more research into the threshold at which physical activity turns from *promoting* growth to *delaying* growth; other studies have identified disordered eating as an additional factor, with up to one-third of females with anorexia nervosa also having persistent osteopenia (Warren 1999; Rosen *et al.* 1999), but the exact nature of the relationship between estrogen production, growth, and menarche are as yet unknown.

To contrast, males have no such event around which development is anchored, and studies of male adolescents focus on comparisons of muscle development and BMD between activities, endurance training, and exercise stress - there is no discussion of “too much” exercise as there is for females. In fact, there is remarkably little on how adolescent males build bone at all; all studies for males from prepuberty to late teens conclude simply that

"BMC and… BMD were higher in the active boys than in the non-active boys" (Cohen *et al* 1995; Vicente-Rodriguez *et al.* 2005: 613). Only one study examined pubertal stage instead of standardising for age, and it found only a weak association between pubertal stage and ability to increase BMD through activity (Nordström *et al.* 1998).

Also detrimental to research in this area is the lack of inter-sex comparisons (Amelia Moore, *pers. comm*). It is well known that changes during puberty turn children – the skeletons of which are indistinguishable between sexes – into skeletally differentiated males and females. As males are generally larger and more robust, they must be forming bone either at an accelerated rate or for a longer period of time than females, but there are no clinical studies comparing adolescent male and female bone formation times; most studies focus on only one sex to eliminate sex as a variable. Other studies examine the sex differences in a particular movement: one such study by Landry *et al.* (2007) investigated the difference in muscle use between males and females in a particular soccer maneuver. They found that females had greater lateral *gastrocnemius* activity as well as greater imbalance between the medial and lateral sides of the *gastrocnemius*; however, the study used males as a basis for comparison and remarked on how the females diverged, and it ended up confirming "common knowledge" that males and females move differently.

Additionally, research goals of studies of adolescent males and females are quite different, with studies of females mostly investigating bone growth for disease prevention while studies of males focus on sport and strength development. This difference between research goals is an impediment to a full understanding of how bone develops in adolescence, which hinders assessment of the range of ancient activity performed by males and females. A common set of findings in studies comparing robusticity across time periods is that differences between females were not significant or that females appear to be performing overall less activity than males despite the time period (Mays 1999; Wanner *et al.* 2007; Pomeroy and Zakrzewski 2009; Nikita *et al.* 2011; Macintosh *et al.* 2014). Perhaps this lack of statistical significance and relative invisibility of women – identified by Conkey and Spector (1984) over thirty years ago – should be further considered in light of the lack of research into inter-sex comparisons. Hypothetically, the shorter pubertal growth spurt penned in by menarche experienced by females limits bone growth while males experience a longer pubertal period allowing more bone growth, which also occurs to a greater extent due to higher levels of testosterone (Arisaka *et al.* 1995; Clarke and Khosla 2009). This hypothesis will be discussed further in Chapter 9 in light of the data collected for this study.

2.6.2 Biomechanics and diaphyseal shape change

In addition to BMD and BMC, a recent development in sports science is shape analysis of the diaphyseal shaft. This section will discuss the ways shape has been investigated in sports science and its relevant applications in archaeology since the 1980s, discussed further in Chapter 4. Note that the ways diaphyseal shape is examined utilizes biomechanical approaches rather than geometric morphometrics, which is also used in this study.

Athletics provides some significant insights into the causes of changing tibial shape. Current researchers can utilize computed tomography (CT) to examine differences in bone shape between athletes of the same or different sports. However, unlike the longitudinal studies above, most rely on a single scan and, although they standardize for age and sex among study participants, cannot rule out additional factors influencing bone shape. The studies discussed above (Lindholm *et al.* 1994; Fujimura *et* al. 1997; Haapasalo *et al.* 1998; Devlin *et al.* 2010) do not examine bone shape but rather bone mineral density, which does not directly influence shape. In fact, it is unclear exactly how bone is laid down in response to stress. Theoretically, there is a threshold at which mechanical loading increases bone formation above ongoing remodeling by augmenting the overall cross-sectional area, slightly above Young's modulus, which as mentioned above may change depending on activity force and frequency (Pearson and Lieberman 2004: 68). Some studies have argued in favor of Frost's Mechanostat hypothesis, stating that increasing speed in bipedal movement results in higher magnitude of strain, inducing an osteogenic response up to a certain threshold at which exhaustion prevents additional bone formation (Lanyon *et al.* 1975; Burr *et al.* 1996; Milgrom *et al.* 2000); other studies suggested that low-magnitude strain can also induce such if repeated often enough, and that as the number of "load-cycles" increases, less strain is needed to produce a response, causing new bone to form in the repetition of daily activities (Rubin and McLeod 1994; McLeod *et al.* 1998; Qin *et al.* 1998).

The most relevant study for this discussion is one conducted by Shaw and Stock (2009), who investigated how habitual activity corresponds to tibial cross-sectional rigidity and tibial diaphysis shape (discussed further in Chapter 4). This investigation of university athletes showed differences in shaft shape between long-distance runners and hockey players who had each participated in that sport at least 10 hours/week from age 12. Considering Shaw and Stock's review of previous studies, it seems likely both theories proposed for bone growth in response to strain are accurate. The repetitive but low-velocity motion of long-distance running as well as the fast and frequent but short-lived movements of field hockey both change the shape, strength, and cortical thickness of the tibial shaft, but in different ways. The paper proposed that the difference in shape may be due to directionality and intensity as well as speed. Long-distance running is performed over a long distance but in a straight line with few changes in speed; field hockey is full of sprints, jumps, lunges, and short "high-intensity" runs at high velocity but for a much shorter total distance than an equivalently timed run. The authors do not discriminate in this study between long-distance running, which is generally on a track, and cross-country running, which covers similar distances but is performed outdoors on variable terrain. Again, recall the implicit assumption of biomechanics: there are muscles driving the bones. Although most of the muscles in the leg are engaged during both these activities, they are utilized a different percent of the time; additionally, the lateral compartment would seem to be more engaged in field hockey due to the frequent side-to-side movement as would the *tibialis anterior* in constant braking. Clearly there are a multitude of factors affecting tibial shape, illustrating the difficulty of assigning activities to ancient populations based on bone form. Similarly, Nikander *et al.* (2008) compared World Cup slalom and mogul skiers. The mogul skiers were found to have a longer antero-posterior diameter and a thicker anterior cortex compared to the slalom skiers. The slalom skiers had more prominent anterior and interosseous crests than the mogul skiers; the latter had more rounded margins. This could potentially be due to stronger forces in the *tibialis anterior* and *tibialis posterior* muscles.

In addition to forces acting on the entire bone, another force that needs to be considered is local loading on the periosteum, discussed above. Despite experiencing very different forces, the tibiae of humans and other terrestrial mammals – including quadrupeds – have a triangular cross-section, shown in Figure 2.6.4.

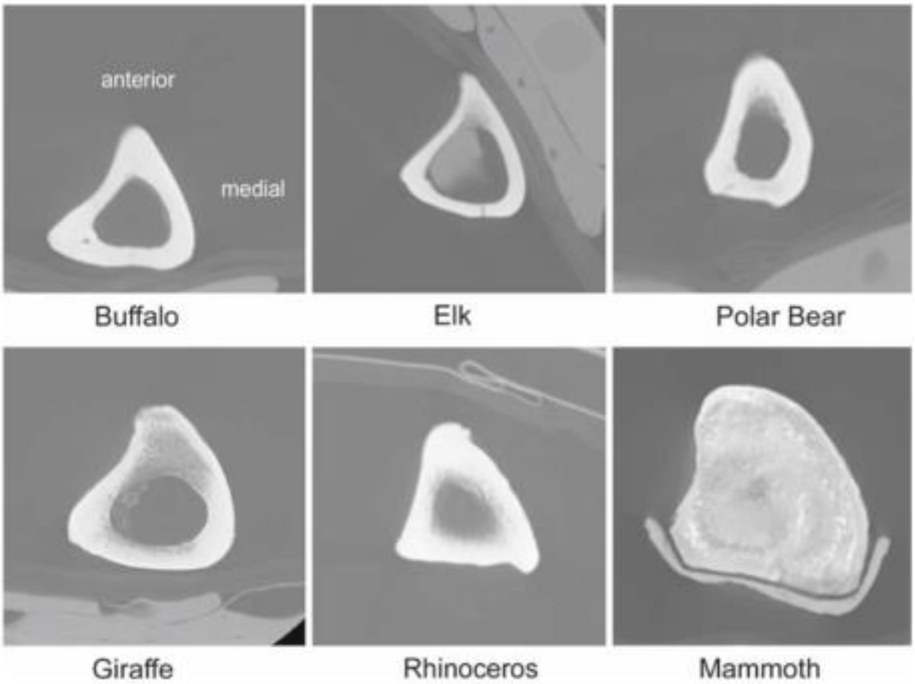


Figure 2.6.4 Cross-sectional CT scans of the tibiae of six terrestrial mammals, showing the roughly triangular shaft shape common to all, as taken from Carpenter and Carter (2008: 228).

The assumption that could be made is that the triangular shaft shape is genetic, originating in hindlimb second axial development alongside thickening of the epiphyseal ends (Hildebrand and Goslow 2001) following from the hypothesis that the shape of bones with a structurally protective function are genetically determined, although bone shapes can be changed at the blastema stage (Amprino 1985). Considering bone functional adaptation, described above, bones with a need to respond to repetitive loading have a basic genetic form but only achieve certain shape characteristics in the presence of that loading, reinforcing a feedback loop wherein the bone architecture is remodeled until it reaches its genetically-prescribed form (Lanyon 1987: 1083). However, research into diaphyseal development complicates this hypothesis, particularly as little data exists. Studies have supported the idea that bones have a genetically-determined shape but that various dimensions and bony features are dependent on growth and use of musculature both before and after maturity (Relethford 2004; Carrier *et al.* 2005; Harvati and Weaver 2006). Additionally, studies of in vivo strain have shown that the direction of a bone's curvature in motion is not necessarily the direction in which remodeling occurs, including concave areas where mechanically one would expect convexity (Lanyon 1980: 457). Carpenter and Carter (2008: 227) point out that the tibia has "flattened, slightly convex, or slightly concave periosteal surfaces at locations adjacent to the muscles of the lower leg" and that the flattened areas correspond to locations where muscle bellies bulge against the adjacent bone. Consider the tibial lateral midshaft, where the convexity anterior to the interosseous crest nestles the belly of the *tibialis anterior*, and the posterior midshaft, where the flattened surface is adjacent to the *soleus* – how exactly do these muscle positions influence the underlying bone?

Further research has shown that adjustments to the surrounding musculature and nerves result in changes to the tibial cross-section. One investigation unilaterally resected (neurectomised) the sciatic nerves of juvenile rats (Lanyon 1980). The sciatic nerve divides into the tibial and common peroneal nerves, which enervate the posterior muscle compartment and anterior and lateral muscle compartment, respectively (Gray 1901: 793; Drake *et al.* 2010: 574); a sciatic neurectomy would restrict the growth of these muscles. The neurectomy caused a unilateral decrease in muscle weight by 40%, bone weight by 87%, and bone width by 89%, but no significant decrease in length. In addition, the leg with the neurectomized (and thus no muscle development or activity) did not form into the typical triangular shape of the antimere with normal muscle development: while it still featured the sharp anterior crest, the outline is rounded instead of sharply triangular (Lanyon 1980: 461), shown in Figure 2.6.5.

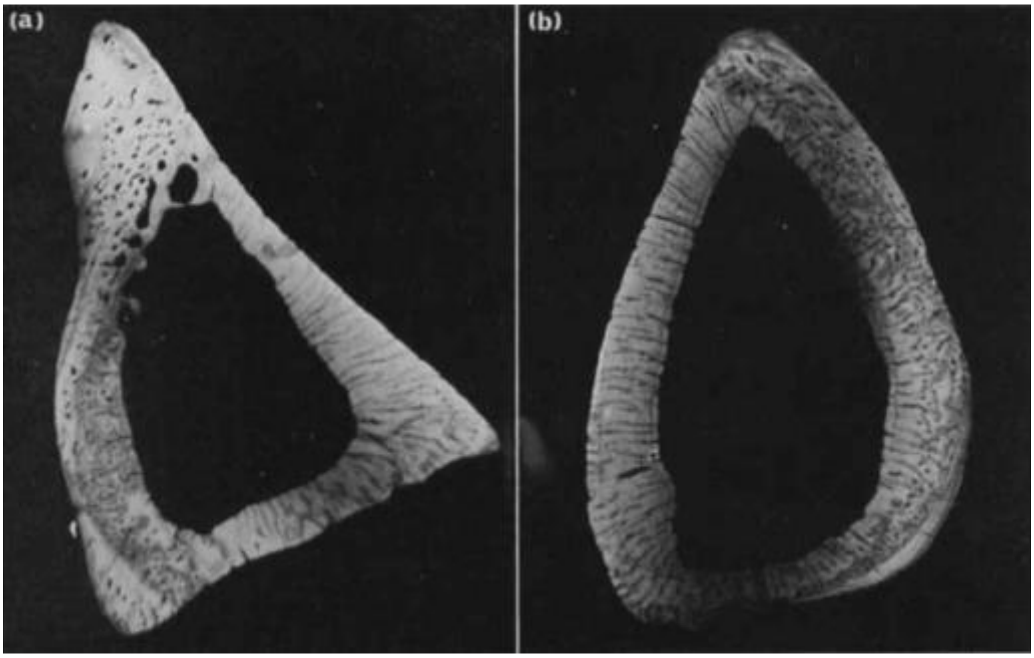


Figure 2.6.5 Microradiographs of the cross-section of left and right tibiae of an individual rat with the sciatic nerve of the right leg neurectomized. The left side has been flipped so that lateral is to the right. Note the rounded shaft shape. As taken from Lanyon (1980: 461).

Lanyon’s preliminary conclusion was that some elements of bone shape are genetically determined, but others are the result of the mechanical environment. Bone length is not influenced by nerve attachments, echoing previous findings that bone functional adaptation is also not dependent on a central nervous connection (1980: 462; Hert *et al.* (1971); but the effect of the sciatic neurectomy on local bone features must be untangled from the suite of changes it induced, namely unbalancing the rat and reducing overall loading. The failure of the tibia to develop a triangular cross-section can be considered a result of the absence of a functional response appropriate to the absence of a stimulus (loading), or a result of an adaptive response “appropriate to the low level of functional stimulus which prevailed” (Lanyon 1980: 462). Lanyon identified this as the accommodation hypothesis: the curvature of the bone shaft accommodates muscle bellies, similar to the way bone accommodates blood vessels, tendons, aneurysms, and tumours pressing into the periosteum. The triangular tibial cross-section may reflect the accommodation for appropriately sized and positioned muscles and ligaments, and the neurectomized rat tibiae did not need to make that accommodation. The bone must make the most accommodation for the posterior muscle compartment containing the digital flexors and tarsal extensors, resulting in a proximal posterior curvature (Lanyon 1980: 463). However, it is still unclear whether it is the lack of stimulus on the bone and muscles as a unit or the lack of muscle pressure on the bone that resulted in the tibial roundedness in cross-section. Carpenter and Carter (2008) used Lanyon's study of rats and similar work to create a computer model of tibial growth in an unloaded state: the results indicated that cross-sectional size is determined mainly by far-field (mechanical) loads and cross-sectional size is determined by local surface loads, such as that of muscle bellies and muscle and tendon attachments. Thus bones do not always reach the predicted optimal shape for resisting and responding to mechanical loads induced by activity, but compromise these loads with accommodations for soft-tissue structures (Carpenter and Carter 2008: 238). This will be explored further in this study by examining human tibiae from archaeological contexts with varying cross-sectional shapes.

This chapter has covered the anatomy of the tibia and its context in the lower leg as well as biomechanical properties and actions of the component parts. It discussed research into how bones remodel with the aim of investigating how human tibias attain their ultimate cross-sectional shapes, considering both mechanical loads produced through specific exercise and activity patterns and local stresses from soft tissue. The next chapter will use these biomechanical concepts introduced here to present an archaeological discussion of activity that will be used to interpret past activity patterns reflected in the human tibia.

3 Defining Activity in Bioarchaeology

This chapter will address the ways researchers investigate activity in bioarchaeological contexts and their research aims. The nonspecific ways the term *activity* can be used in comparison to the terms *work* and *labour*, particularly in archaeological investigation, will be discussed first. These terms refer to separate concepts which will be specifically defined in this chapter in order to clarify the research presented here. Section 3.2 addresses how much activity makes an impact on bone, drawing from recent research in sport science (Shaw and Stock 2009; Nikander *et al.* 2010), and to what extent this activity can be seen archaeologically considering differing research methods and taphonomic processes. The following three sections discuss results from three lines of investigation utilising biomechanics to explore activity in the archaeological record that are relevant to the current project. These will investigate the way cross-sectional geometry, robusticity, and shape have been used to examine differences between the sexes, between social classes, and between groups practicing different subsistence strategies. The limitations associated with defining these categories, particularly subsistence strategy, are addressed as well. Brief reviews of several relevant studies are included. Section 3.6 discusses theories of sedentism and nomadism in general with reference to anthropological research and why these are important factors to consider in the Sudanese setting. Class-, economy-, and ethnicity-based reasons for nomadism and the difficulty of identifying these archaeologically are introduced. A final discussion will cover constraints in current methods and suggested caveats and methods to rectify these.

3.1 Defining "activity" archaeologically

This section will define what is meant by "activity" when discussing human remains in archaeological contexts and distinguish how its use differs from *work, labour,* and *exercise*. These terms are commonly used interchangeably but each have a unique meaning with regard to human motions that leave evidence on the skeleton. It is important to note that not every form of activity affects the skeleton and not every type of activity is work or labour, and that they often connote a post-industrial idea of work that is different from how it might be conceived in non-agricultural societies.

Work and Labour

Generally, discussions of structures of divided or stratified labour in antiquity refer only to productive work: farming, shepherding, fishing, and hunting with regard to food production. Later, "professions" that emerge alongside urban development and changes in communal structure are included (Lee 1968; Byrd 1994). However, these practices define work in line with a Western, modern view as productive activity, focusing on the necessarily public work that enables society as a whole to function, with a great emphasis on modes of food security and production, and – if following a traditionally Western differentiation of public and private spheres - ignores or denies most of the contributions of women and the private sphere. An example is Lee's ethnographic work on the !Kung San (1979: 259), which considers all public foraging activities to be work and thus estimates the hunter-gatherer workweek to be 2.6 days, while ignoring the additional 3 days spent processing food in the private sphere. Anthropological and ethnographic work does explore the role of women's contributions to survival, particularly in foraging and pastoral communities (Claasen 1991; Jackson 1991; Fratkin *et al.* 1999). These studies include not only work that directly affects survival but also those of cultural transmission – storytelling, teaching, tool making, cooking. In addition, ethnographic studies often find that men and women can participate in both productive and cultural work together (Evans-Pritchard 1940), but when they are separated anthropological researchers have tended to focus on male contributions, leading to the hunter-gatherer differentiation: that is, men are hunters and women are gatherers, and the primary focus of the ethnography is on hunting as it results in the most visually graphic work (Conkey and Spector 1984; Handsman 1991). When compared to hunting for large game or trapping for small game, gathering – which uses few tools besides a digging implement – is glossed over, seen as uninteresting and less skilled (Weedman 2006), likely due to gathering's association with women and the private/domestic sphere. On the contrary: in 20th-century foraging communities, gathering accounted for at least 50% and up to 95% of the society's caloric intake (Cordain *et al.* 2000; Pontzer *et al.* 2012), and sufficiently more time and energy was spent gathering plants than hunting animals. The historic bias against women's work and the focus on man-as-hunter often obscures this fact. Also obscured is the fact that men (and children) also gather, as shown in Lee (1979). Thus work has been defined differently depending on the researcher and the context, but generally has been used to mean activity related to food acquisition and production. Work is one type of activity that will be examined here in an archaeological context as contributing to bone formation and shape.

Exercise

In addition to productive work and cultural transmission, there are also activities of daily life and leisure. Although "leisure time" is claimed by some researchers (Rojek 2013) to be a post-industrial construct, there is evidence from antiquity of games, sports, contests, fairs, and relaxation in a number of societies (Lowerston and Myerscough 1977; McLean *et al.* 2004; Rojek *et al.* 2006). Whether it was construed as leisure or as ceremony either by the society practicing it or by outside observers is irrelevant: only that it was practiced. Religious ceremonies can also be included in this category. Exercise also receives mention in a number of texts from the ancient world as part of education and citizenship, most notably in the case of the ancient Greek Olympic games, ritual/religious games which grew out of funeral games for local heroes and an educational philosophy that promoted perfecting the body as well as the mind to promote happiness and civic responsibility (Aristotle trans. 2004; Swaddling 1980; McLean *et al.* 2004). Exercise can be defined as athletic or competitive activities that specifically focus on working muscle groups and overall bodily exertion in order to achieve a physical goal. Various researchers have examined who has access to these games, sports, and exercise, usually from a modern perspective (Rojek 1985; McLean *et al.* 2004; Rojek 2013), but one must consider that pre-industrial societies had differing practices with regard to work versus leisure, with numerous festival days and "unofficial" practices. Arguing that sport was only practiced by the elite is akin to arguing that football is only played in Premier League matches and not by children or amateurs. Even Aristotle (trans. 2015) commented on leisure time in the ancient world as part of the systems of power, arguing that the Egyptian rulers kept workers labouring on the pyramids to make them too tired to consider revolt, clearly not considering Deir al-Medina, where workers spent their "free time" painting their own tombs or current ideas of pyramid-builders as off-season labour (Lesko 1994; Conard and Lehner 2001). In fact, as Toohey and Veal (2007) pointed out, men of lower classes were not barred from the ancient Olympic games as long as they were freeborn citizens and celebrated as victors if they won, although the training requirements made participation difficult within an agricultural labour framework; however, a complaint was made in 416 BC that "the games were being overtaken by the lower classes" (Toohey and Veal 2007: 20). It is important for researchers not to rule out athletic activity as a factor inducing bone shape change, despite potential class indicators. However unimportant to survival or social functioning they may seem, leisure activities and exercise – practiced for long enough – constitute an important activity that contributes to bone development.

Body positioning

Finally, there are activities so commonplace that they are often left unmentioned but nevertheless contribute to bone formation and shape. These are the ways an individual uses their body in motion and at rest: walking, sleeping, sitting, eating. Whether one sits in chairs or squats on the ground has an impact on leg and pelvic development (Lovejoy *et al.* 1976; Shefelbine *et al.* 2002). Frequency of walking in early childhood changes the femoral bicondylar angle, discussed above. Culturally constructed ways of holding the body in space take up a significant amount of person-hours (for instance, compare hours sleeping vs. hours working) and thus should be considered activities in their own right. Posture while sitting and standing are included, as are styles of dress or ornamentation that limit or amplify movements or postures. In a study of Arikara female sitting practices before and after adoption of chairs, femoral torsion differed between the two periods (Wescott *et al.* 2014). This pattern of femoral torsion was only seen on female skeletons (shown in Figure 3.1), as side-sitting was only required for women and not men or young children. Modes of transportation are also activities requiring analysis. Whether one walks, runs, or rides a donkey to perform work at a location secondary to the home will impact the skeleton, especially if one carries additional materials or infants in the arms or uses bags or packs (Fowler *et al.* 2006; Gillette *et al.* 2009).

Figure 3.1 Crow women side-sitting on the ground with legs pointed to the right, resulting in greater femoral torsion than sitting in chairs. As taken from Wescott (2014: 521).

For this current project, activity will be defined as any culturally-based movement that potentially has an effect on the musculoskeletal system. It need not result in food, capital, or social gains and may even be deleterious to life, as in the instances of overuse resulting in pathological developments; lack of movement, in the case of infants, the elderly, or disabled, can also constitute a culturally-constructed activity that can lead to bone resorption or a lack of development (Leblanc and Schneider 1991; Kiebzak 1991). Ultimately, bone responds to any movement or lack of movement in a predictable way (Pearson and Lieberman 2004), so activity must be defined here in terms of bone reaction. This study seeks to understand not only labour as defined above but any differences in activity that are practiced by discrete groups: bone shape can identify a variety of practices unrelated to occupation, and describing findings in terms of labour alone is limiting.

3.2 How much activity has an impact?

A problem that arises when studying bony reactions to activity is how much activity an individual needs to perform to have an impact. Psychological studies show that modern humans tend to overestimate the amount of time spent "working productively" and underestimate the amount of time spent on leisure activities, particularly sedentary ones; for example, a recent study found that British people underestimate the amount of time spent watching television by one-third (Sallis and Saelens 2000; BBC 2011). It is now possible to track activity, heart rate, and energy expenditure accurately on a large scale using personal tracking devices, a process which has been tested on both North American urban consumers and Tanzanian foragers (Pontzer *et al.* 2012; Raichlen *et al.* 2014). Research on amount of time spent on an activity needs to be combined with research into bone building and turnover, particularly in nonclinical human studies rather than the animal studies often used to demonstrate osteoblastic activity (Mazess and Whedon 1983; Salem *et al.* 1993; Wallace *et al.* 2015; Barak *et al.* 2011). If researchers could match bone remodeling rates to other physiological effects related to activity, studies of exercise-induced bone change can increase in specificity, increasing accuracy when investigating archaeological skeletons whose activity practices are at this point only conjecture.

Studies such as Shaw and Stock's (2009), which examined living male athletes, found that the athletes had regular practices, often along the lines of "1.5h/session, 5 sessions/wk, 12 months/year" (151), which totals 390 hours of their selected sport per year. Nikander *et al.* (2008) examined competitive skiers, who practiced over 15 hours per week but only in winter. In a different study, Nikander *et al.* (2010) examined female athletes in both load-bearing and non-load-bearing sports: the amount of practice varied between 7 and 17 hours per week. Haapasalo *et al.* (1998) examined peripubertal female tennis players, finding that females over approximately 15 years had played tennis for an average of 1131 hours over their careers. Each of these studies found significant differences in either bone shape, bone mineral density, or bone mineral content between the athletes and controls, who had practiced strenuous activity for 3 hours per week or less. Considering there are over 5000 waking hours per year, 390 hours per year or 1131 hours over 4-5 years is not a very high percentage, and it is difficult (if not impossible) to compare hours spent on athletics practice to activity practiced in ancient societies of any type. Additionally, the studies do not explore other factors that could contribute to bone building, such as walking as a means of transport and whether the time spent away from sports is active (standing) or passive (sitting). Clearly it would be impossible to include all of these factors in a study.

What is the threshold for increased bone turnover? Apparently the answer is somewhere between 3 and 7.5 hours of strenuous activity per week, although the definition of strenuous is not consistently defined in athletics research. In many sports studies it is defined by heart rate or caloric expenditure or rely on self-definition by the subjects (Blair *et al.* 2001), but these are not relevant when considering bone biomechanics as the key factor in increased bone turnover is not heart rate but whether and to what extent an activity is load-bearing (Jend *et al.* 1985; Drapeau and Streeter 2006). Thus cycling and jogging practiced by the same individual at paces matched to equivalent heart rates, but jogging resulted in increased bone remodeling as it is load-bearing and involves direct ground reaction forces (Morseth *et al.* 2011).

Considering the types of activity practiced in ancient societies – Sudan in particular – there is a distinct lack of non-load-bearing activities. All bipedal activities involve some degree of load-bearing, and even riding donkeys and horses (once introduced) as a means of transport is load-bearing on the spine and pelvis. Agricultural activities in the fields are load-bearing (Gillette *et al.* 2009; McMillan 2014), as are grain processing and grinding. Most foraging activities are also load bearing. These include walking, running, and digging, many of which are similar to movements within farming, but practiced with greater regularity and intensity. In fact, the lower physical workload of agriculture could account for the gracility of modern humans (Ryan and Shaw 2015). Thus one can consider all activity involving movement for this era and region to be load-bearing and have an effect on one or more bones. Studies of agricultural, pastoral, and foraging activities will be discussed further to break down the type of effect these might have on various parts of the skeleton, and whether they were performed by differing members of society dependent on age, sex, status, or other social divisions. As there are to date no studies of activity for Meroitic and post-Meroitic Sudan, studies of other archaeological sites across the Sahel, into southern Africa, and Egypt will be considered. These are also relevant as climate and subsistence patterns have shifted over time and still vary widely within this area (Adams 1997; Ginter 2011); additionally, the type of activities practiced in subsistence societies varies widely and are not strictly limited to subsistence work, as discussed above.

3.3 Differentiating male and female roles through bioarchaeology

This section will present several case studies from archaeological research demonstrating differences in activity based on sex. It is important to note that this will only cover biological sex as assessed by pelvic and/or cranial traits and not gender, which is a socially-constructed identity that refers to biological sex and social presentation (Conkey and Spector 1984). While many societies worldwide correlate female/woman and male/man, these are the two ends of a spectrum which also includes intermediate points on both the sex and gender axes. Often, skeletal sex is difficult to assign due to age of the individual, fragmentary nature of the remains, or assemblage-wide variation: for example, Sudanese and sub-Saharan males tend to have more gracile skulls than European males (Lahr 1996) potentially causing confusion to a researcher inexperienced at assessing sex in Sudanese skeletal remains but leading those more experienced to add more weight to sexual assessment of the pelvis (when preserved). In many archaeological cases, sex was assigned based on burial artifacts, which we now understand to be more associated with social ideas of gender presentation (Conkey and Spector 1984). Little has been written about sex and gender in ancient Sudan, but Egypt seemed to use a two-gender model with masculine- and feminine-associated behaviours and artifacts (Sweeney 2011). Unfortunately, many of the grave goods in the Meroitic and post-Meroitic periods were not associated with a particular skeletal sex; ceramic bowls and jars, jewelry, and small metal items were found in many graves but diminish in the early Christian period (Edwards 2007; Soler 2012). It is also possible that any luxury items associated with a specific sex were robbed in antiquity (Derek Welsby *pers. comm.)*.

One way of distinguishing male and female activity through skeletal analysis is examination of musculoskeletal markers, known as MSMs or, in marked cases of erosive lesions at sites of ligamentous attachment, enthesopathies (Hawkey and Merbs 1995; Robb 1998). Comparisons between males and females have been made for a number of sites worldwide (Churchill and Morris 1998; Porcic and Stefanovic 2009; Villotte *et al.* 2010). These compare the robusticity of musculoskeletal markers using a system wherein a smooth attachment is indicative of a low level of activity and a more robust attachment is indicative of a higher level of activity. Asymmetrical MSM robusticity or a significantly differing rate between males and females indicates different types of activity: many motions used in labour, especially considering handedness and footedness, result in asymmetrical stress on the musculoskeletal system. By analyzing which MSMs are more robust, bioarchaeologists can hypothetically isolate which muscles or muscle groups were used and associate these with a particular activity (Robb 1998; Robb *et al.* 2001). It should be noted that recent research has attempted to refine MSM scoring methods as well as raise further issues with the Hawkey and Merbs system, noting the impact of age and that different types of entheses exhibit stress variably (Villotte *et al.* 2010; Jurmain *et al.* 2011; Henderson *et al.* 2012; Villotte and Knüsel 2013).

An early possible example of sex-based division of labour is seen at Tel Abu Hureyra in Syria, inhabited between 11,500 and 10,000 BP (the pre-pottery Neolithic), and again in the early Neolithic, although the original study was later found to be problematic. Botanical evidence includes remains of wild grasses, seeds, and pulses in the early period and more domesticated plants in the later period, although both include wild faunal remains (Molleson 1994: 71). A great number of skeletal changes were found at the site, including enlarged neural spines in the cervical vertebrae, enlarged mandibular condyles, and beveled posterior tooth wear, indicating carrying; arthritic great toes, increased MSMs in the upper arms, buttressing on the anterior distal femur, and vertebral collapse of the twelfth thoracic, indicating work with the arms in a toe-dorsiflexed forward-leaning squat (Molleson 1994: 72, see Figure 4.3).

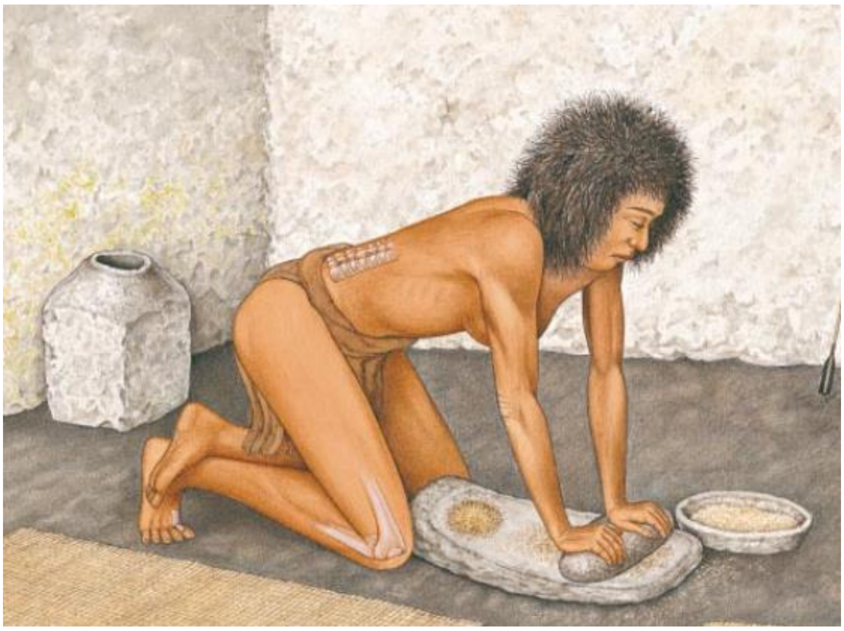


Figure 3.3 Illustration of a Tel Abu Hureyra woman grinding grain with affected bones highlighted. The position is similar to (or modeled after) an Egyptian figurine published in Breasted (1948). As taken from Molleson (1994: 70), copyright Scientific American.

The particular arm motion is thus described by Molleson:

> “[S]he pushes the stone toward the far end of the quern, ending the stroke with her upper body almost parallel to the ground so her arms are at or near the level of her head. On reaching the far end of the quern, she jerks back to her starting position. I call this part of the grinding action the recoil. The movement that raises the arms as the grinder pushes forward employs the deltoid muscles of the shoulder. During this stroke, the arms also turn inward, a motion accomplished by the biceps muscles. It is precisely the places where the deltoid muscles attach to the humerus … and the biceps muscles to the radius … that are markedly developed in these individuals. The overdevelopment of the muscles was symmetrical, affecting both arms equally. On the forearm of these individuals, the radial tuberosity—the bulged area of the radius where the biceps muscle attaches—is particularly noticeable.” (Molleson 1994: 72)

Molleson connects these MSMs and pathological changes of the vertebrae to grinding with a mortar and pestle and saddle quern, noting that the injuries to the toes and vertebrae only occur when the saddle quern is placed on the ground, and this pattern of injury is not seen alongside similar MSMs at Çatalhöyük, where querns were placed on plinths while grinding (Molleson 2000; Molleson and Rosas 2012). Although sex assessment was difficult due to fragmentation, researchers identified those individuals with these patterns of MSMs and injury as females, indicating a division of labor wherein males hunted and gathered and later cultivated while females processed the yield. Another craft-related change – striations in the anterior teeth from fiber processing – was seen in female skeletons. Females tended to be buried below household floors in greater numbers than males (Nelson 2007), which could also signify the advent of the *women-household* connection or, contrarily, the *male-public/female-private* dichotomy. Critique of Molleson's argument and data by Gilchrist (1999) and Crabtree (2007), which highlighted concerns with extrapolating social developments from MSMs using only female skeletons, will be discussed in section 3.6.

Similar grain-grinding MSMs have been found in the Southwest US, despite a different working position: Perry (2004: 199) noted an association between Puebloan females and robusticity at the humeral *teres major* and *coracobrachialis* attachments as well as ligamentous attachments at the clavicle. The researcher pointed out that ethnographers witnessed women grinding corn from peripuberty for many hours a day, and advanced age was also correlated with MSM robusticity. Additionally, females had greater robusticity than males at MSM sites associated with pottery production, notably the *pronator* muscles, *brachialis*, *brachioradialis*, and *abductor* and *adductor pollucis* (Perry 2004: 202) – all of which are used in smaller, wrist- and finger-based household work and increase with age. Young males were significantly less robust at these locations than young females or older males (Perry 2004: 204).

Churchill and Morris (1998) investigated foraging behavior in the prehistoric Khoisan (South Africa) by comparing MSMs with optimal foraging theory. This approach argues that robusticity varies with caloric cost of various food items in the local environment, arguing that forest and fynbos[2] Khoisan (approximately 2000 BP) had greater search costs and thus greater lifetime work intensity than coastal savanna Khoisan (approximately 4000 BP), leading to increased robusticity given similar food processing practices. Eight sites of muscle attachment were examined, including the soleal line, and only adults of similar age category were compared. Differences in robusticity were greater between the two biomes for males than for females (Churchill and Morris 1998: 401). This aligns with historical records of the San, who had gendered division of labour: females primarily gathered marine resources while males hunted land animals using a variety of methods including burning and traps. Lower limb robusticity was higher in forest and fynbos males than coastal savanna males, and they had a lower femoral neck shaft angle indicating greater mobility earlier in life (Churchill and Morris 1998: 401). Differences in upper limb robusticity were more significant, possibly due to handling (processing and butchering) costs of savanna flora and fauna, but once again only among males (Churchill and Morris 1998: 401). While this type of microeconomic-evolutionary method was able to predict robusticity, it was not able to completely explain the upper limb differences given similar processing techniques seen in the archaeological and historical record and do not fully explain the nature of male and female roles. The caveat discussed in more depth below about female muscle and bone building may well apply: if females do not build bone as rapidly as males, they might not be comparable when examining the amount of activity performed.

MSMs can be examined in conjunction with activity-related skeletal degeneration. Sofaer Derevenski (2000) compared changes to male and female vertebral facets between Ensay, an early modern site in the Hebrides, with Wharram Percy, a medieval Yorkshire town. From historical records, these two sites had differing male and female labour roles: at Ensay, women carried out the bulk of the heavy labour, including digging and transporting peat, in addition to domestic work while men performed agricultural tasks; at Wharram Percy, gender roles were more loosely prescribed, but women tended to perform much of the work inside the home and men performing more laborious tasks aided by oxen (2000:

---

[2] A unique arid environment in the Western Cape region of South Africa (Churchill and Morris 1998).

349). Sofaer Derevenski found remodeling of vertebral apophyseal facets and osteophytes in different locations along the spine: Ensay females primarily had upper thoracic changes but not lower, while males experienced degenerative changes throughout the thoracic region. Males and females from Wharram Percy were equally regionally affected, although males had a higher frequency of cases (Sofaer Derevenski 2000: 350). This suggests the similarity of work between sexes at Wharram Percy and differential work at Ensay (Sofaer Derevenski 2000: 352).

However, there are caveats for using MSMs to examine sex- or gender-based differences in activity. Hormonal differences between males and females, particularly during puberty, result in females building bone and muscle at a slower rate and putatively to a lesser extent than males. Despite recent controversies within athletics over conditions like androgen-insensitivity syndrome and other hormonal variations from the purported norm enhancing female muscle growth and thus performance (Epstein 2013), the chance of finding and identifying these archaeologically is slight. Robb *et al.* (2001) point out that body size and muscle mass are sexually dimorphic and may affect MSM rates, and if hormones are taken out of consideration, males should have stronger MSM in the lower limb due to carrying increased body weight; however, sexual dimorphism is more distinct in the upper limbs (Robb *et al.* 2001: 220). Little research in modern athletes or controls has examined comparative muscle- and bone-building rates between males and females, particularly around the peripubertal period: without pubertal hormones, children have similar rates of bone density and musculature, but once in adulthood comparison becomes difficult due to lack of a baseline measurement (Grimston *et al.* 1993). The effect of androgens, including testosterone, on bone and muscle development is to add mass easily (Bradney *et al.* 1998; Lorentzon *et al.* 2005), an effect studied in modern athletes involved in doping scandals, transgender and/or transsexual athletes, as well as in pubertal males (Lapauw *et al.* 2008; Van Caenegem *et al.* 2012). It is possible that given the same amount of training hours, a female athlete will not build muscle or bone as fast as a male athlete, or her muscle mass will peak at a lower level than a male's. This results in less robusticity of MSMs in females and could lead researchers to conclude that females were participating in lower levels of activity. In addition, the MSM scoring system relies on poorly-defined scalar analyses based on written descriptions and unclear photographs, and does not differentiate between fibrous and fibrocartilaginous entheses. Finally, increased MSM robusticity tends to be strongly correlated with advanced age, which should be noted in a mixed- or unknown-age sample (Jurmain *et al.* 2011; Villotte and Knüsel 2013). A proposal to ameliorate the effects of this would be to use high/low criteria when scoring MSMs, comparing highly-scoring females to highly-scoring males. The New Coimbra method, developed recently, is more specific in terms of describing entheseal changes and has low rates of inter-observer error, but is necessarily a much more complex scoring system (Henderson *et al.* 2013; Henderson *et al.* 2016).

Finally, examination of diaphyseal shape could aid in investigating male and female roles, as hypothesised in this project. Bone remodeling in response to activity is similarly spurred by testosterone, but is also responsive to body weight and intensity of activity. Using individuals as controls against themselves by examining axial vs. appendicular skeletal elements or antimeres in unilateral activities shows that shape and density changes occur in response to activity regardless of sex (Haapasalo *et al.* 1998), although more studies examining males and females together need to be conducted. It is promising as an additional factor to consider in MSM studies.

3.4 Social stratification reflected in activity

Social status is used to mean to social role or roles an individual or group holds in society (Appadurai 1986); economically, this can be stratified based on financial or material wealth. In cemeteries with little or no written evidence, social status can be hypothesised based on evidence from grave goods, coffin or grave type, burial position, and – in Christian cemeteries such as 3-J-18 – proximity to a church (Roberts *et al.* 1989; Mays 1998; Ginns 2010b). Social stratification has commonly been assessed by examination of grave type (Binford 1971; Carr 1995), but social stratification can also be seen archaeologically even without the aid of grave goods indicating status. Individuals of different social sectors had different labour requirements, with the burden of work generally falling on lower classes.

These individuals are the closest to the means of production and in an agricultural or industrial setting are those responsible for the majority of resource acquisition and processing (McGuire 1983; Marx and Engels 2014). Researchers expect to see differential patterns of MSMs not only between males and females, but also between elites and non-elites within a society. As opposed to discussing activity as a whole, it is easier to discuss labour specifically in this case. In dynastic Egypt, there is written evidence of numerous classes within society, each of which completed different types of labour: priests, artisans, and farmers each performed different movements associated with labour for differing amounts of time (Trigger 1983; Stock *et al.* 2011; Lloyd 2014). Within the farming and artisan group, there may be sub-sectors based on ability or familial ties. Researchers expect to see different types of MSMs in each group, and generally more MSM robusticity overall for those participating in heavy labour (Villotte *et al.* 2010).

To this aim, Robb *et al.* (2001) and Robb (1998) conducted research on individuals interred in the Pontecagnano necropolis in Italy dating from the 7th century BC to the 4th century AD, the Italian Iron Age. As few individuals were buried with grave goods indicative of occupation, quantity of grave goods and grave type (tiled versus simple pits) were used as an indicator of status. The males were easily distinguished into a high-status group and a low-status group; the latter had higher frequencies of Schmorl's nodes, trauma, and periosteal reactions. While generally similar with regard to MSMs, the elite males had higher scores for upper limb musculature (Robb *et al.* 2001: 219). However, the authors point out that "there is no obvious candidate for an activity involving these specific muscles, and it is not immediately clear whether the groups apparently of higher social standing should have been more active, less active, or active at different activities than their lower status fellows" (Robb 1998: 375), and offered the explanation that there are more types of social wealth divisions than an elevated elite and an oppressed underclass. This is important: when researchers categorize graves as only "elite/non-elite", they may be overlooking subtler social divisions and making assumptions about the type of labour performed by each group. Additionally, researchers expect to see different patterns of MSMs in assemblages where social stratification takes different patterns (Robb *et al.* 2001). In pastoral societies, there may be a social hierarchy (or in some cases, perceived ethnic differences) between herders of caprines and herders of cattle, but they participate in many of the same tasks: thus they would be indistinguishable bioarchaeologically (Bradley 1992).

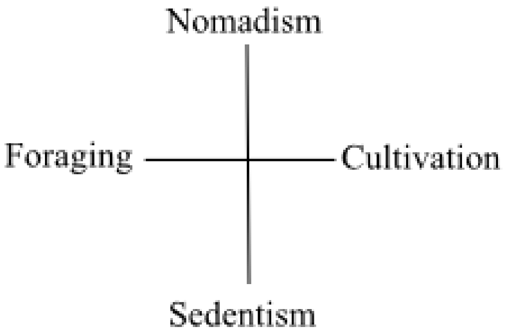
Further, it should be noted that extensive MSMs may not exclusively be markers of activity. Rogers and Waldron's (2001) study of diffuse idiopathic spinal hyperostosis (DISH) identifies it as connected to "the monastic way of life" – that is, overeating and drinking alcohol – and can be seen in individuals from Merton Priory and Wells Cathedral from the 13th-16th centuries. One of the diagnostic criteria for DISH is extraspinal ligamentous ossification, pictured on the patellae and calcaneus in Figure 3.4. Thus not all MSMs are the direct result of activity, but may have a pathological origin (in this case, a status-based pathology).

Figure 3.4 DISH-associated MSMs on the patellae (top) and calcaneus. As taken from Rogers and Waldron (2001: 358).

3.5 Subsistence strategy reflected in activity

Subsistence strategy generally refers to the method by which cultural groups acquire provisions (Chang and Koster 1986; Cribb 1991). The general terms used are “hunter-gatherer”, meaning all foodstuffs are acquired by foraging and hunting for wild game, “pastoralist”, meaning a reliance on domesticated livestock, and “agriculturalist”, meaning a reliance on cultivation. It is important to recognise that these systems are neither mutually exclusive nor reflective of mobility, but more reflective of the Western desire to categorise or “lump” behavioural categories (Chang and Koster, 1986), and Khazanov argued that “classification for the sake of classification is, of course, nonsense … no one anthropological classification can accommodate the entire multiplicity of specific cases” (1994: 18). It should be noted that “subsistence strategy” itself is a problematic term and, as many of the cases below illustrate, a better phrase might be “mode of production” as the groups are often interdependent and do not necessarily subsist on what they produce.

Alongside the transition to agriculture came increased settlement in urban areas. With seasonal crop systems and less need to roam in search of new foraging areas, areas with enough moisture and land could support growing populations. Wengrow (2010) suggests that the new urban centres featured the first sedentary populations. However, one sedentary settlement does not mean that all individuals in that sphere of influence lived sedentary lives, and Lees and Bates (1974) argued that nomadic pastoralism was a reaction to sedentism as an economic specialisation necessary for expansion. Mobility across a landscape is a separate element from subsistence strategy, with true nomadism, or constant change of location, on one end of a spectrum and sedentism, or full maintenance of a permanent habitation, on the other. They can be plotted as such (Cribb 1991; Bradley 1992; Price and Gebauer 1995):



Thus it is possible to have a categorization such as "sedentary hunter-gatherer", such as the Hadza of Tanzania (Woodburn 1968; Murray *et al.* 2001). There are examples of groups that do not fit neatly into the paradigm, such as the Achuar of the Upper Amazon, who cultivate and harvest crops but hunt for meat (Ingold 1996), the semi-sedentary foraging Ohlone tribes in the San Francisco bay (Kroeber 1962; Jones 2015), and the seasonally sedentary hunting and fishing Ertebølle of Denmark, who also utilised domesticated pigs in some periods (Enghoff 1986; Richter and Noe-Nygaard 2003). Pastoralism does not fit into a particular niche, as both foragers and agriculturalists can utilise domesticated livestock. Fishing is also difficult to place: is it true gathering? Fishing often requires either the use of textiles (rope, baskets) or remodeling of the environment (weirs, dams), which are arguably more complex than picking vegetables (Peters and den Driesch 1993): it should, however, be said that picking vegetables requires a considerable degree of knowledge as well – where to go, which are available given seasonal variation, which are not poisonous. One must also consider the amount of mobility groups or individuals have around the landscape. A foraging society with a central base must travel a significant distance outward to gather resources (Pontzer *et al.* 2012), which may equal the amount traveled by pastoralists grazing livestock; a study of the Sukuma in Tanzania showed that they traveled between 500 m and 4 km away from home to water their herds, depending on the season, and occasionally up to 9 km (Coppolillo 2000: 540). In terms of amount of distance traveled, Binford (1980) distinguished foragers with high residential mobility, or movement between sites, from those with low logistical mobility, or movement away from camp in search of food, possibly dependent on climate (Pearson 2000). Agriculturalists may not travel as far but may perform more local (in-place) high-energy activity such as ploughing. Conversely, they may travel to fields spread across a broad area due to local land use and ownership practices. This creates a sort of paradox - as stated above, researchers have found diminished skeletal robusticity worldwide with the transitions to agriculture, but ethnographic literature reports increased activity with a stronger dependence on agriculture. Are farmers actually performing more activity than pastoralists and foragers? The skeletal evidence does not appear to support this idea. Perhaps nutrition plays a role, with decreased protein and increased carbohydrate intake affecting bone remodeling; another proposal is human domestication, wherein humans both reduce in size and decrease in sexual dimorphism as a result of the unconscious selection pressures of living in villages (Leach 2003). The latter includes the former as a factor in size reduction.

Mobility, like subsistence, falls along a spectrum. The spectrum in this case ranges from "truly nomadic" to "truly sedentary". A commonly seen group, particularly in the Sahel and North Africa, are the nomadic pastoralists, who spend a considerable amount of time as nomads in order to graze domesticated cattle, sheep, or goats. Cavalli-Sforza (1996) advances the theory that nomadic pastoralism originated as a secondary development to farming in regions where full agriculture could not sustain a high population of humans but could support animals with seasonal movements. Cattle became one of the most successful domesticates due to their secondary outputs of milk, leather, and traction (Sherratt 1983; Cavalli-Sforza 1996), and "cattle cultures" such as Kerma built up immense wealth in cattle. Other researchers propose either passive or active reasons for groups to take up nomadic pastoralism. Adams *et al.* (1974) asserted that nomadic pastoralism was a fallback strategy for those unable to cope with the transition to agriculture, and Irons (1975) argued that the growth of urban centres increased the need for pastoral products, thus driving some individuals to become pastoral specialists, on the basis of evidence from the Zagros highlands. Khazanov (1994: xl) cited ethnographic and historical evidence that pastoralism existed only after animal domestication, thus necessitating some form of agriculture to kick-start the pastoral process. It could, in fact, have occurred the other way around, with the network of nomadic pastoralists converging seasonal camps and cultivation centres into urbanised, semi-permanent (or truly permanent) settlements, though archaeologists are unable to differentiate between these seasonal camps and those belonging to a more permanent group with a transhumant sub-sector. Cribb (1991) summarised further arguments, but in truth the origins of nomadic pastoralism differ by region and time period. For the Sahel and Nubia, climate change must definitely be considered in addition to the advent of agriculture.

The question regarding mobility, particularly pertaining to nomadic pastoralists, is how many days must be spent in a single location to qualify a group as semi-sedentary, and how many days roaming to be considered nomadic? Nomadism is considered here as a level of mobility rather than an economic strategy, a debate explicated by Khazanov (1994). This has bearing on the question above – how much activity is needed to induce bone remodeling, and can bone remodeling be seen as the result of nomadic strategies? Cribb (1991) defined true nomadism as a complete lack of reliance on agriculture and is thus isolated to a small number of groups in the Eurasian highlands and steppes, Arabia, and the Sahara – environments unable to support any agriculture; he further argues that searching for pure nomadism should be abandoned in favor of identifying nomadic tendencies in groups assigned to other categories. Fernandez-Gimenez and Le Febre (2006: 349) defined true nomadism as erratic, patternless movements, as opposed to seasonal transhumance. Thus many societies often described as nomadic are essentially semi-nomadic or semi-sedentary. Khazanov (1994: 19) defined *pastoral nomadism* proper as "characterized by absence of agriculture, even in a supplementary capacity" – an economic rather than movement-based classification. Kerma itself had a great city, but the number of cattle (as evidenced by the royal tumuli) to support that population could not have spent every season so close to the urban centre. Cribb continued to define nomads as either tied, that is, fixed to a certain route, or untied, true wanderers. As discussed by Bradley (1992), nomads often have a fixed ceremonial burial site that they may return to seasonally, making many ancient Nubians presumably tied semi-nomads. Crabtree (2007: 238) identified three types of pastoralism: pastoral nomads, who practice no agriculture and move herds seasonally; transhumant pastoralists, who combine fixed field agriculture with some community members moving herds seasonally; and agropastoralists, who combine agriculture and husbandry in permanent locations. Johnson (2002) has further subdivided pastoral nomadism into three distinct modes based on the criteria of mobility, biomass availability, and dependence on wild food:

- Agropastoralism: individuals employ mixed subsistence strategy, have moderate mobility, occupy habitats with a biomass greater than or equal to 1500 g/m²/yr, and consume less than 20% foraged or acquired plant foods
- Subsistence pastoralism: individuals rely on small stock, travel up to 100 km/year and less than 10 times/year, occupy a habitat with a biomass exceeding 500 g/m²/yr, and rely on 20-40% foraged goods and have no investment in agriculture. All individuals participate in herding activities.
- Economic specialism: individuals rely on over 40% foods acquired through trading or foraging, are highly mobile, and occupy habitats with less than 500 g/m²/yr in available biomass. If agriculture exists, it is class-based with slaves performing agricultural labour, and herding tasks are divided by age, gender, or class.

Thus nomadism is reflective of environmental availability while pastoralism is determined by reliance on utilization of dairy and meat from herding; thus dietary dependence on pastoral products is inversely correlated with dependence on wild plant foods, and mobility is inversely correlated with dependence on acquired plant foods (Porcic 2008; Johnson 2002). In addition, Johnson identified other markers of each type, including marriage patterns and dispute resolution that stem from their degree of reliance on trade.

What of societies split into groups where some practice nomadic pastoralism and some sedentary cultivation – how are they defined? These divisions have implications for tibial shape in the archaeological record. Bradley (1992) described a village in the Nile-Atbara region in which one ethnicity remains sedentary year-round while another practices a nomadic lifestyle seasonally but still maintain camps in the village, and Cribb (1991) described an Afghani Pashtun community in which some families are pastoral and some agricultural. Similar systems exist at the margins of the Malian Inland Niger Delta and across the Sahel (Gallais 1984; Toulmin 1992). McCorkle (1987) discussed Quechua villagers in Peru who have the option of becoming herders or remaining in the village to fulfill agriculture roles. Khazanov described a multiplicity of divisions in northern Africa:

> "In the Libyan (Western) desert of Egypt the Jawabis tribe as a whole participates in both agriculture and pastoralism … But in the same desert there are other tribes which are divided in two sections: one section leading a relatively sedentary way of life, the other a fully nomadic one. Nevertheless, both sections are parts of a single unity under one sheikh." (1994: 20)

In addition, Sahelian cattle-based cultures fluctuated in their level of nomadism: as they gained more cattle, they became more nomadic in order to graze them, but in the event of a loss of their herd they might settle in a village to farm and rebuild their stock; thus one generation may be nomadic and the next sedentary (Bradley 1992; Brass 2001; Moritz 2013). Additionally, amount of distance traveled depends on access to water and seasonal grazing lands (Coppolillo 2000). Khazanov problematised the tendency to define these societies as "pastoral nomadic" and suggested that researchers discuss them in terms of professional specialisation and division of labour (1994: 18). All of these aspects of mobility potentially have bearing on lower limb diaphyseal shape, which is why knowing the amount and type of activity performed by individuals or groups within a society is valuable in bioarchaeological analyses.

However, there are many reasons for shifts between nomadism and sedentism: Bradley (1992) also depicted families in which the parents are of different ethnicities, and one has had to relinquish their traditional subsistence pattern, so ethnicity and subsistence are not always one to one. Cribb also discussed changing government policy, political instability or war, and population growth of humans or livestock as factors in shifting patterns of nomadism seen in the Near East ethnographically, all of which are applicable to the Kerma and Meroitic periods (refer to Chapter 6.2). Further, McIntosh's description of the ancient Middle Niger (2005) emphasises the pluralistic nature of a large city. Subsistence-defined ethnic groups congregate in one venue as an agglomerated society, but each maintains their own identity and distinctive level of mobility, leaving or entering the city as they require for trade purposes or to follow seasonal resources. Further, Khazanov argued that from an economic (or arguably caloric) perspective, nomadic pastoralism and semi-nomadic pastoralism are interdependent and the former is often practiced in concert with some level of agriculture (1994: 20). In the Sudanese case discussed later in this research, Kerma and

Meroë may have had divisions of labour akin to those of Jenne-Jeno, and the evidence of immigrants moving into Wadi Halfa supports the hypothesis of a segmented society (Buzon 2006; Buzon and Bowen 2010).

Research must also consider age and gender when considering labour breakdown (Gilchrist 1999; Crabtree 2007). Data on time-allocation for agricultural groups varies worldwide depending on the type and intensity of agriculture, available technology, and water availability, which will be discussed later in this chapter in the context of Sudanese water wheels.

For pastoralists in a late 20th-century East African context, a gender-based division of labor exists with regard to type of animal herded. Among the Sukuma in Tanzania, discussed briefly above (Coppolillo 2000), boys and men herded cattle while women and girls herded goats, sheep, and donkeys (Peter Coppolillo, unpublished data). Considering divisions of labour separating groups into nomadic and semi-nomadic, Khazanov listed a number of situations in which the men move whilst herding livestock but the women remain sedentary. Among the latter type are the Jie and Karimojong in East Africa and the Fulani and Teda in the Sahara; the Jie have the proverb “grain is the stock of women” (1994: 20). The explanation frequently given for this gendered labor is that the men are needed to protect the cattle on longer journeys, as they graze further from the homestead, and that women are needed for the more intensive garden crop cultivation which also occurs around the home (Little 2001; Coppolillo *pers. comm.*), although this appears to be a post-hoc description and, as shown below, is not always true. Likewise, Biagetti (*pers. comm.*) reports that among the Tuareg it is the men and boys who herd cattle. In an assessment of a variety of mobile pastoral groups worldwide, (Fernandez-Gimenez and Le Febre, 2006) found a variety of roles based on age and gender:

- in Kyrgyz, Kyrgyzstan, men hunted and herded and women produced dairy products and made felt (Fernandez-Gimenez and Le Febre 2006: 344)
- among the Fulani (Ivory Coast), children guarded the milk herd and men herded the mobile animals (Fernandez-Gimenez and Le Febre 2006: 345)

- at a variety of locations in East Africa, young men and women herded cattle and camels and children herded small stock
- among the Fulbe (Mali), young men herded the mobile cattle and old men guarded the milk cows (Fernandez-Gimenez and Le Febre 2006: 345)
- among the Hadza (Tanzania), men hunted game with small bows and gathered honey alone while women gathered plant material in groups with digging sticks; these gathering practices were reflected in differing diets for men and women with men eating more meat (Murray *et al.* 2001: 10), but still 80% of the Hadza diet was comprised of vegetable matter, mostly tubers and berries (Woodburn 1968: 51). Men walked around 11.4 km±2.1 per day and women walked around 5.8 km±1.7 per day, and 95% of caloric intake was based on wild food sources (Pontzer *et al.* 2012: 4) – despite covering less distance, women accounted for a higher proportion of the total food produced.

However, Fernandez-Gimenez and Le Febre point out that there is significant flexibility inherent in pastoralism, and that depending on the season, climate, rain, grazing availability, and market conditions, pastoral groups may focus more on one type of livestock or crop cultivation, which has implications for interpreting social roles archaeologically. Roles in this region seem to be roughly assigned but not necessarily fixed. It is important to note that most of the ethnographic studies on time-allocation and activity are in response to changing conditions – political or institutional, environmental, and economic (Fernandez-Gimenez and Le Febre 2006: 341) – and thus should not be over-interpreted as the way mobile pastoralism has always been practiced in an East African or Sahelian context. These studies indicated that mobile pastoral ways of life changed in the later 20th century and should be used to show the variety of gender- and age-based roles in different societies.

While complex, subsistence strategy has been examined bioarchaeologically. Studies of the Neolithic transition in the past decade have focused on biomechanics and diaphyseal morphology instead of (or in addition to) MSMs, and this study continues to examine differences in diaphyseal morphology. Stock and Pinhasi (2011) explored a number of bioarchaeological changes that accompanied the transition towards domesticated plants and animals, including reduced craniofacial morphology, increasing dental and skeletal pathology, and changes in limb diaphyseal shape within and between assemblages due to changing patterns of activity.

In one of the earlier studies utilising cross-sectional geometry, Ruff *et al.* (1984) investigated the effect of the transition to agriculture on the Georgia coast (USA) on femoral midshaft shape and robusticity. Agriculture was adopted much later in the Americas than in Africa, Asia, and Europe, in this case around 1150 AD (Ruff *et al.* 1984: 126). Samples were all young adults, although it is unclear whether they were chosen to alleviate the problem of correlating age with increased robusticity or if age at death was very low in these groups. The researchers found a decline in all cross-sectional properties in the agricultural period for both sexes, but significantly greater decline for females. Bending strength (used as a proxy for shape) did not change significantly, although female femora became rounder in the subtrochanteric region (Ruff *et al.* 1984: 132). Additionally, the area inside the medullary cavity decreased, resulting in a thinner cortex which is consistent with decreased stress (See Figure 3.5).

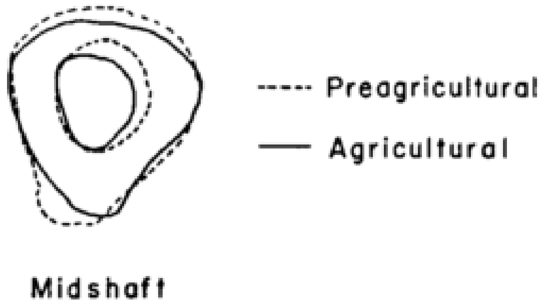


Figure 3.5 Femoral midshaft in preagricultural and agricultural groups on the Georgia coast. As taken from Ruff *et al.* (1984: 132).

This study, along with Ruff and Hayes' (1983b) work on Pecos Pueblo, was foundational in establishing cross-sectional geometry as a method of investigating ancient activity and mobility. Only direct sectioning was available then, so unfortunately results cannot be replicated for these sites.

Macintosh *et al.* (2014) examined the transition to agriculture in Europe between the early Neolithic and early Medieval periods through tibial and femoral cross-sectional geometry. In the male tibial midshaft, all cross-sectional geometric properties decreased over time; for females, cross-sectional geometric properties decreased over time, but the femur increased slightly in total area (2014: 385). Sexual dimorphism was higher for all values in the Neolithic and Bronze Age with significantly larger males, but decreased significantly in the Iron Age and Medieval periods. Another finding was the regional variation in male tibial bending strength but not female. Macintosh *et al.* noted that the transition to agriculture was not purely a change in subsistence strategy: increased crop yields – and thus increased total calories available – led to higher populations, the beginning of urban centres that included individuals of mixed backgrounds and activities, metallurgy, changes in mobility across landscapes, and altered divisions of labour including task and craft specialization (Macintosh *et al.* 2014: 385). The trend towards gracility of the lower limbs, particularly among males, is typical of the rise of agriculture. With less need to travel long distances to obtain food, lower robusticity is seen. However, as Molleson (2000) has shown, significant sexual dimorphism in other areas of robusticity can still be seen. With regard to shape, a number of researchers have investigated either variation between temporally-separated groups in similar environments or change in response to environment (Ruff *et al.* 1984; Nikita *et al.* 2011; Shaw and Stock 2013; Wescott *et al.* 2014), which will be discussed with regard to the tibia in Chapter 4.

Again, these are changes that need to be examined over an entire assemblage, as opposed to studies of sexual or social differences in activity, which can be compared within one assemblage. Not every member of a group was practicing the same types of activity, but by utilising biomechanical and geometric morphometric data it is possible to compare overall bone shape statistically and produce average shapes for males, females, and skeletons of indeterminate sex, as this study will demonstrate.

Marchi (2008) examined change in tibial and femoral midshaft shape in response to possible changes in subsistence strategy between the Late Upper Paleolithic, the Ligurian

Neolithic, and the Eneolithic. Previous studies showed a decrease in femoral bending strength and a rounding of the femoral shaft from the Early Upper Paleolithic to Mesolithic, which was interpreted as a response to decreased mobility, aligning with archaeological data suggesting a decline in resource reliability and increases in regional diversification and population density (Marchi 2008: 188). This change in femoral shape and strength appears to be characteristic of the hunter-gatherer to agriculturalist shift, discussed above in Macintosh *et al.* (2014). Additionally, researchers argue that this shift involved a change in sexual division of labor. Ruff (1987) and others found a decrease in sexual dimorphism of leg strength with the advent of agriculture, purportedly because male hunters stopped traveling long distances to hunt or herd and joined females in more sedentary tasks such as vegetable gathering and processing. Marchi (2008) found the Ligurian individuals were more similar to the earlier Palaeolithic groups than to the Neolithic, with high levels of sexual dimorphism including less circular tibial diaphyses and a thicker midshaft cortical area (2008: 194). The Ligurians were not hunter-gatherers but sedentary pastoralists and both sexes were quite robust. However, according the study, the males did the bulk of the work involving travel. Despite a shorter time between the Eneolithic and the Ligurian than between the Ligurian and the Late Upper Paleolithic, the population changed more drastically. The sudden decreases in sexual dimorphism and tibial rigidity implies a quicker change from pastoralism to agriculturalism than from hunting and gathering to pastoralism, and also that this shift involved changes to the sexual division of labor (Marchi 2008: 196). This conclusion has been confirmed by a later study (Marchi *et al.* 2011). As with Macintosh *et al.* (2014), Marchi's work involves shape indices, which calculate the circularity of a bone. This is a useful metric for the roughly-circular femur and humerus if the linea aspera is not overly robust, but tends to fall short for the roughly-triangular (or diamond-shaped, as discussed in Chapter 7.7) tibia.

Nikita *et al.* (2011) investigated tibial robusticity and cross-sectional geometry around the Sahara region, using individuals from Jebel Moya (also used in this study), Kerma, el-Badari in Egypt, and Garama in Libya. The Garamantes inhabited the central Sahara at a time when it was stabilising into the desert climate as it exists today and are probably descended from mobile pastoralists (Nikita *et al.* 2011: 423). Over three phases from 900

BC-500 AD, the urban centre was developed around irrigation agriculture and trans-Saharan trade networks were established. By the time the cemetery under study was established, the Garamantes were agriculturalists using subterranean water channels. The researchers found sexual dimorphism was present in all assemblages studied, but among the Garamantes was only significant in the lower limbs (Nikita *et al.* 2011: 429). Femoral bending strength was most similar between the Garamantes and el-Badari. Lower limb asymmetry, which will also be investigated in this study, was low in the Garamantes and Kerma, the agricultural groups, and high in el-Badari and Jebel Moya, the pastoral groups (Nikita *et al.* 2011: 428). However, as the present study shows, only nine Jebel Moya individuals had both tibiae preserved to test asymmetry. The Garamantes also had higher asymmetry among males than females. Another finding was the similarity between Garama and el-Badari in lower-limb cross-sectional total area and robusticity; the researchers postulated that the uneven terrain around Garama could be a previously-unconsidered factor in studies of cross-sectional geometry and mobility (Nikita *et al.* 2011: 430). Shape indices were also calculated as in Marchi (2008) and Macintosh *et al.* (2014).

Stock *et al.* (2011) have further explored habitual activity in the Nile Valley, comparing the humerus and femur at el-Badari with Hierakonpolis, Kerma, and the much older Jebel Sahaba, from the Upper Palaeolithic. This latter group had the highest levels of long-bone diaphyseal rigidity as well as high levels of sexual dimorphism in both long bone strength and stature (Stock *et al.* 2011: 25). The trend continued into el-Badari and the agricultural groups, with decreasing humeral rigidity in females. There was overall much more variation in all humeral and femoral variables examined for males, which, considering the above caveats in examining female metrics, is understandable and should be taken into consideration in future studies.

The above researchers investigated cross-sectional geometry as a proxy for shape, but did not directly examine shape differences. Morphometric examination of individual and group shape differences, examined in this study, will increase the amount of data retrievable from each bone and ideally provide a clearer picture of activity through comparisons to modern human activities in addition to comparative numerical assessments.

3.6 Critique

This chapter has covered a number of previous studies of biomechanical applications to archaeology that are relevant in the Sudanese case. However, their shortcomings must be addressed. As stated above, a weakness of most research is not considering the multitude of factors that go into bone building and turnover. A common tendency is to suppose males and females are equal in bone building when studies of modern humans find this is not the case. Due to hormonal differences, not only do females build bone at a slower rate than males, they also lose bone at an earlier age and can experience pregnancy, which has the potential to decrease bone mineral content. Finding that females have lower total cross-sectional area, rigidity, bending strength, or robusticity than males at a given site does not necessarily mean that they were doing overall less activity. While this current work may be subject to the same methodological concerns as similar research, the conclusions will note that these interpretations of the data are subject to a proposed understanding of bone remodeling differentiated by sex.

Similarly, activity is not the only cause of bone growth. The converse to the above is that males might be larger and more robust due to the effect of testosterone on bone and muscle growth on sexual dimorphism. In addition to pathological excessive bone growth seen in rare conditions like Paget's disease of bone, ankylosing spondylitis, and the above-mentioned DISH, Waldron (2009) estimates that up to one-fifth of all individuals are "bone-formers", a quantity which has also been suggested in clinical literature (Rogers *et al.* 1997; Mays 2016). These individuals are more likely to produce heterotopic ossification and to ossify cartilage and entheses; any pathology that causes excessive bone growth will result in "particularly exuberant" bone growth (Waldron 2009: 72). It is inaccurate to regard those individuals with the most robusticity and the highest overall rates of enthesophytes as the most active in a skeletal assemblage when it is also possible they are bone-formers.

There is also a problem with over-interpretation of data. Many studies use small sample sizes – particularly those that use the el-Badari and Garama collections, which only have 4 and 7 usable individuals, respectively (Nikita *et al.* 2011: 427). This is often inevitable when working with poorly preserved archaeological assemblages.

There is significant critique of the Abu Hureyra study, both from a bioarchaeological perspective and as a model for the early Neolithic. Molleson does not distinguish from which period the 87 studied individuals came over the 3000-year span of the site, nor does she extend comment to activity-related MSMs in the male skeletons; her dental study only examines 17 individuals (Molleson *et al.* 1993), so it is possible the total examined for the MSM study was less than 87, and the study was mostly descriptive with no inter-site comparison with other pre-pottery Neolithic sites or skeletal material from later known agriculture sites or statistical analysis. As a model for gender roles, Molleson's evidence for division of labour is based only on the work of females, and there is no equivalent MSM identifying males as cultivators or hunters (Crabtree 2007: 246). The support for the argument that women come solely from Gilchrist notes that Molleson's argument is "self-fulfilling: an exclusive sexual division of labor is expected … the possibility of more flexible, seasonal, and perhaps age-based divisions of labour are not considered" (1999: 44), failing to include the role of children and adolescents, who were shown to have also carried heavy loads on their heads (Molleson 1994: 71). Crabtree points out that none of the data highlight the role of anyone at Abu Hureyra in animal husbandry; considering a key question of the Epipaleolithic-Neolithic transition asks how gazelle hunters were transformed into herders, the Abu Hureyra study falls short in this regard, instead emphasising only the expectations of female roles in this era (Crabtree 2007: 247). The extent that the skeletons of Abu Hureyra – or any one site – can be used as evidence for shifting gender roles is thus limited.

Keeping these methods of investigation and critiques in mind, the next chapter will discuss how the tibia in particular has been used to interpret activity patterns in ancient and modern humans.

4 Using Tibial Morphology to Infer Activity in Past and Current Populations

In the last century, tibial morphology has been extensively researched by anatomists, archaeologists, and anthropologists (Ruff and Larsen 2014). The tibia is the second-largest bone in the human body and, comparatively, tends to preserve well, and its morphology has been the focus of more archaeological and evolutionary research than the smaller human bones. As discussed below, researchers have used comparative tibial morphology to formulate arguments about the behaviour and genetics of archaic *Homo* species and anatomically modern humans. Recent studies have examined tibiae from archaeological assemblages and living humans, finding differences in tibial cross-sectional geometric properties between archaeological time periods, and associations between cross-sectional geometric properties and current sports practices. The former are used to suggest that differences are visible in the long term; the latter reinforces how these changes to the tibia can also occur over the human lifespan. This chapter discusses the historical research of tibiae to highlight the changing aims of bioarchaeological research and addresses why tibiae continue to be important to current investigations into ancient activity.

4.1 Historical studies

This section covers historical research on the tibia from the 19th-20th centuries, focusing on its importance to the cnemic index categorization of human types. The study of the tibia has been important in arguments for human bipedalism, human exceptionalism, and the anthropological eugenics movement before biomechanically-based bone turnover was accepted scientifically. While the current study aims to add to research of bone turnover, previous arguments within the field must be addressed as they have shaped the way researchers approached the topic.

4.1.1 Historical analysis: the cnemic index and cultural classifications

Described in Martin's Lehrbuch der Anthropologie (1914), the cnemic index defines the amount of mediolateral flattening of the tibial shaft at the nutrient foramen (Martin 1914; Bass 2004). The index is a ratio between the mediolateral and anteroposterior diameters:

$$\frac{\text{Medio-lateral diameter}}{\text{Antero-posterior diameter}} \quad * \quad 100$$

Individuals are divided into hyperplatycnemic, platycnemic, mesocnemic, or eurycnemic (Bass 2004), shown in Table 4.1.1, based on sectioning points possibly derived from standard deviations from a mean eurycnemic tibia, but the original assemblage used to create the index has not been recorded. The higher the index, the rounder the shaft; the lower the index, the closer the shaft is to flat with anterior and posterior crests. This remains the principle of some of the cross-sectional geometric ratios which will be discussed in Chapter 7.4.

Category	**Minimum**	**Maximum**
Hyperplatycnemic	-	54.9
Platycnemic	55.0	62.9
Mesocnemic	63.0	69.9
Eurycnemic (Eucnemic)	70.0	-

Table 4.1.1 Sectioning points for the cnemic index, as taken from Bass (2004).

Earlier work by George Busk recorded tibial mediolateral flattening in Gibraltar in 1863 (Busk 1869; Lucas 2007) in combination with extreme robustness of the soleal line and *linea aspera* on the femur and very thick cortical bone. In the 1870s, he proposed that platycnemia was a mark of a “rugged and energetic lifestyle,” an idea that quickly caught on in the scientific community. Researchers began to notice platycnemic tibiae at archaeological sites worldwide. Debate at the time centered on the evolution of man, and platycnemia and platymeria – antero-posterior flattening of the femur – among ancient humans seemed to hold a clue towards the move to bipedalism. The first platycnemic ancient population studied was discovered in Wales, with W. Boyd Dawkins and Busk examining at the insistence of Charles Darwin. Busk noted that "all the tibiae are more or less compressed or platycnemic" and that many of them showed quite robust muscle attachments (Lucas 2007: 327).

In the early days of its discovery, there was disagreement over whether platycnemia was pathological (rickettsial) or could be used as a marker of "race" or of "advanced civilisation". Dawkins proposed that "platycnemism also is a character that has not been recognised in any human remains later than that age [the Neolithic]" (Dawkins and Busk 1870: 449). Busk noted that although the "normal" (that is, modern) English tibia had an index of 70-80 and those from Wales had an index below 70 (with a mean of 61.1), too many other populations – notably the Cro-Magnon skeletons and those of North American mound builders – had platycnemia to use it as a true marker of race (Dawkins and Busk 1870: 459). Populations could not be so easily divided by the cnemic index. After seeing evidence of platycnemism among the mound builders and "among negroes… and even among civilised Europeans" (Dawkins 1880: 313), Dawkins seemed to agree with Busk and Darwin.

Paul Broca's extensive study of the platycnemic Cro-Magnon tibias from Eyzies, France (1868; 1880) reveals the scientific debate at the time. He notices that the flattened shape of the Cro-Magnon tibias, while having corresponding elements to modern triangular tibias, are more like those of anthropoid apes. He extensively refutes his colleague Franz-Ignaz Pruner-Bey's hypothesis that the tibias are rickettsial as they are thickened but not curved, and have a length greater than many modern humans, at an estimated maximum of 410 mm. His refutation does suggest that there could be a "fossil pathology" unknown to modern humans, but it is absent from the Eyzies specimens, who appear healthy apart from traumatic injuries. Additionally, he is possibly the first anthropological researcher to comment on muscle development in response to activity, noting that "in particular the extraordinary projection of the *linea aspera* of the femur, testify to the great development of muscle power" (Broca 1880: 39). His attempt to reconcile the Cro-Magnon's dolicocephalic skulls – which differed greatly from the recently-discovered Neanderthals – with their robust bodies and flattened tibias but advanced brains, resulted in a rather unique environmentally deterministic approach, placing them as slowly succeeding in a struggle of brains over brawn:

> "The cavemen from Eyzies were therefore barbarians, like all men of their time, and it is not surprising that these conditions of their existence have left strong impressions on their skeletons. But the barbarians were intelligent and improved, and while continuing their struggle against nature and against man itself, they knew how to create sufficient leisure to increase their knowledge, to develop their industry and, even more, to develop arts and culture. All valuable skills, … but truly extraordinary given the time in which they have arisen, [which] favor a beautiful brain organization, expressed morphologically on the skulls of the race of Eyzies." (Broca 1880: 40)[3]

He places the Cro-Magnon collection as a unique "race" rather than an extension of the presumed (much later) Neolithic Aryan group his colleagues were trying to shoehorn them into. Pruner-Bey, convinced that all dolichocephalic individuals were Aryan, believed the Cro-Magnons from Eyzies were ancient Estonians and ignored any differences in tibias or even direct skull measurements (Sommer 2007).

Both Busk (1869) and Dawkins (1870) noted that platycnemia was associated with pilasterism, or extreme robusticity of the *linea aspera*. Anatomist William Turner also noticed platymeria in some platycnemic populations and thought there must not be a racial or even population-specific reason but rather mechanical, in an early move against the adaptationist paradigm. He proposed that femoral platymeria "must have some relation to the attachment of the muscles in this region and to the traction which, in connection their use [sic], they would exercise on the bone in its plastic and growing state" (Turner 1895). He also notes that he was wrong in connecting platymeria to squatting, and that the only

---

[3] Translations author's own from French original

cause can be exercise. Note that he reached this conclusion three years after the proposal of Wolff's Law, discussed previously in Chapter 2.5. Thus the consensus was that platycnemia and platymeria were caused by habitual activities, of which the most frequently suggested was squatting, possibly because it was considered a "primitive activity" (Buxton 1938).

In the 20th century, most researchers of platycnemia spent more time attempting to prove the hypotheses suggested in the 19th century than coming up with new hypotheses to explain platycnemia (Pearson and Lieberman 2004; Barak *et al.* 2011). Although the idea of bone change in response to activity had been proposed in 1892 (Wolff 1892), it took around 80 years for researchers to implement it in a serious study of tibial shaft morphology. More recently, approaches have combined biomechanics theories with the genetic potential for bones to attain certain morphological variations (Renaud *et al.* 2010; Delgado-Calle *et al.* 2012). Emphasis has also shifted from pure platycnemia to the entire shape of the diaphysis, and focus has been returned to habitual exercise as a cause of alterations in morphology.

Most researchers in the early 20th century tended to believe that platycnemia was due to some combination of lifestyle and bone chemistry while still accepting that it is somehow primitive. In 1914, Martin still wrote that racial groups were generally either eury-, meso- or platycnemic, but suggested that these shapes were caused by some action of the *tibialis posterior* or interosseous ligament. Cameron argued in 1934 that platymeria and platycnemia are due to "unwonted strain during childhood and early adolescence", particularly of "the undue prominence of" *tibialis posterior* (Cameron 1934; Buxton 1938: 31) and that the index decreases with age. Buxton, dissatisfied with Cameron's answers, examined flattening of the femur, tibia, humerus, and radius in ten different populations with inconclusive results. In the case of the Romano-British population, Buxton observed an association between flattening of the tibia and flattening of the femur but a dissociation between flattening of the humerus and radius; this makes sense in consideration of later understanding of biomechanics and use of one's limbs (Buxton 1938: 34). Additionally, he measured the area and perimeter of sectioned bones on the belief that "less actual bone substance is required in the construction of the shaft of a flattened bone than of a cylindrical one… assuming the area for muscles is kept practically constant" (Buxton 1938: 35), which indicates an understanding of the principles of bone turnover and conservation of energy, neither of which had yet been proposed. He found this to be true: bones of a similar size but different indices had the same perimeter but differed in area. The reason he gave for this decrease in area is a bone deficiency, possibly a lack of calcium or vitamins, which aligns with his argument that platycnemia is found in "primitive peoples."

The decades after Buxton's and Cameron's articles were published witnessed a huge increase in knowledge about bone biology and genetics as well as many changes to the archaeological paradigm. This encompassed the decline of adaptationist views of evolution,[4] which were replaced with the study of evolutionary development and genetics and the rise of processualism, which attempted to make archaeology more science-focused and described culture using some of the same terms as biologists used for organic systems (Johnson 2010; Sherwood and Duren 2013). This was used in biological and physical anthropology as evolutionary developmental biology, which "examines evolutionary transformations of the processes by which the genotype generates phenotype" (Pearson and Lieberman 2004: 64; see also Hildebrand and Goslow 2001). As Pearson and Lieberman explain, this approach provides insight into the developmental processes of the skeleton and also "highlights the degree to which features in the skeleton are intrinsically integrated at different hierarchies of development" (Pearson and Lieberman 2004: 64), encouraging researchers to look at the skeleton holistically rather than as a series of independent traits. The result of these developments, both practical and theoretical, is that the study of platycnemia as an end in itself was largely ignored in favor of examining the shape of the shaft as a whole; yet anteroposterior and mediolateral diameters at the tibial nutrient foramen are still recorded. As late as the 1980s, investigations concerning platycnemia were still underway (Alan Morris, *pers. comm.*); while platycnemia was found across many

---

[4] Adaptationism attempts to distinguish which features evolved through adaptations versus those that are byproducts or due to random variation. See Gould and Lewontin (1979).

Southern African groups, it was found to be unconnected to nutritional stress during growth (Morris 1986; Ledger *et al.* 2000).

4.1.2 Hrdlička and diaphyseal shapes

An additional researcher of note is Ales Hrdlička, whose goal was to explore both differences between types or races of men as well as human development from an ontological as well as evolutionary perspective (Sherwood and Duren 2013). This included measurements of all types on both living humans and skeletal remains. Section 3 of the principal work on anthropometry (Hrdlička 1920) defined all the measurements researchers can take from the postcranial skeleton, which has been influential on bioarchaeology since. He argued that the middle of long bones was the best for differentiating shape (Hrdlička 1920: 121). Hrdlička defined a number of shapes of long bones based on measurements and direct sectioning. Most relevant here are his descriptions of the tibial midshaft in cross-section, shown in Figure 4.1.2 and described below:

- Type I is prismatic or triangular and is the typical shape of all long bone diaphyses
- Type II is called the "oblique" or lateral prismatic, and is a half-lozenge with a flattened posterior surface
- Type III has a lateral concave surface and a medial convex surface
- Type IV features an additional surface, a vertical ridge on the posterior surface, noted above as the posterior buttress
- Type V has a convex posterior surface and an indistinct medial border
- Type VI is plano-convex and called "gorilloid" (Hrdlička 1920: 129).

It is unknown which population or assemblage Hrdlička used to derive these shapes and whether they were of normal distribution. In the six shape categories identified in Chapter 7.7 and utilised in this study, Hrdlička's II was not seen, but another (identified as "droplet") was observed, mostly in females. It is possible that the assemblage Hrdlička studied was either quite different from the assemblages examined here, or possibly contained only males. Hrdlička did not suggest a use for these shape categories, nor was there a suggested origin or reason for differential shapes.

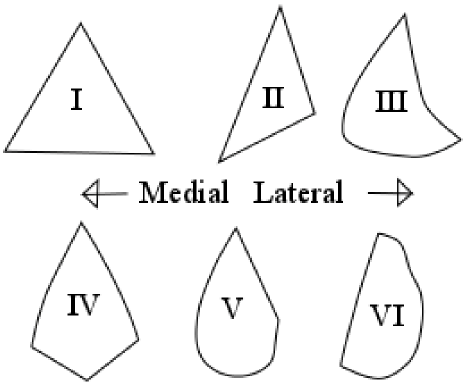
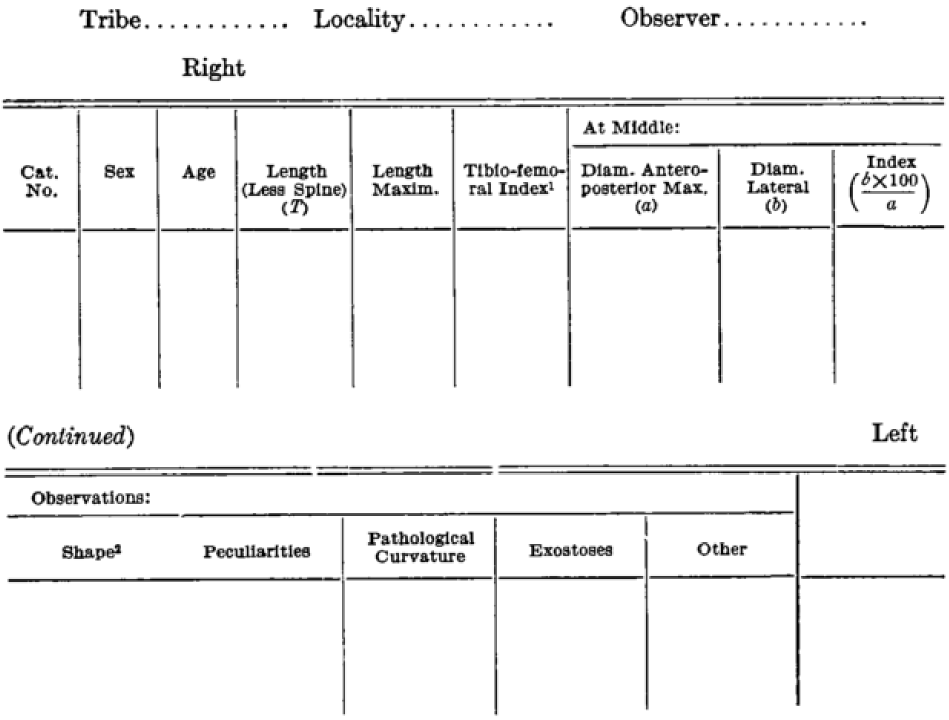


Figure 4.1.2 Illustration of midshaft tibial shapes by S. Hackner 2016, after Hrdlička (1920).

Hrdlička defined flatness (platycnemia) as an independent occurrence unrelated to the six shape types, and argued that tibial mediolateral flatness is accompanied by fibular mediolateral and femoral anteroposterior flatness (Hrdlička 1920). While noting that there are fewer shape types in fetuses and children, he reasoned that most bone shape variability is heritable and each shape occurs with different frequency in different races. He admitted that sex, body size, and muscular activity may also have an effect, and that differences between racial groups are partly due to occupation (Hrdlička 1920: 124). Muscle markers are also discussed, and he argued them to be "partly hereditary, partly early acquired" and that "the manner in which the differently attached or differently developed muscles affect the shape of bone must of course be largely if not entirely mechanical" (Hrdlička 1920: 126). Hrdlička instructs bone researchers to record the index at midshaft, ignoring the cnemic index altogether, shown in Figure 4.1.3.



Tribe............ Locality............ Observer............

Right

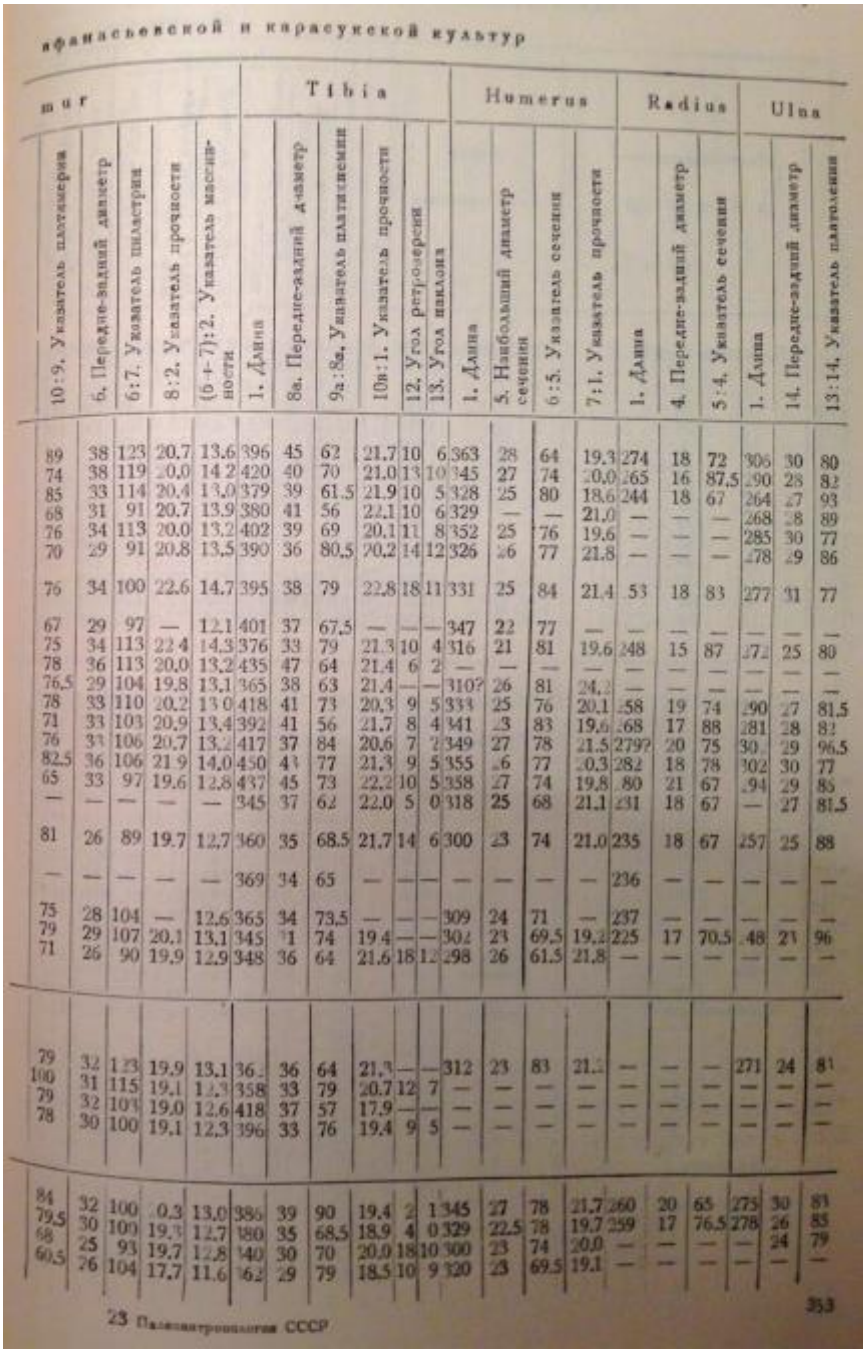
						At Middle:		
Cat. No.	Sex	Age	Length (Less Spine) (*T*)	Length Maxim.	Tibio-femoral Index[1]	Diam. Antero-posterior Max. (*a*)	Diam. Lateral (*b*)	Index $\left(\frac{b\times100}{a}\right)$

(*Continued*) Left

Observations:					
Shape[2]	Peculiarities	Pathological Curvature	Exostoses	Other	

Figure 4.1.3 Recording blanks for the tibia, as taken from Hrdlička (1920: 129).

However, researchers did not utilise Hrdlička's recommendation of measurement at the tibial midshaft and continued to measure at the nutrient foramen (an example illustrating the use of the cnemic index even outside of Europe is shown in Figure 4.1.4). Bass's updated osteological field manual instructs researchers to measure the tibia's length and diameters at the nutrient foramen (Bass 2004: 247), despite the midshaft's significance as the point of maximal biomechanical stress. The benefit of the nutrient foramen is that researchers can use it as a point of measurement in cases where one or both epiphyses are missing or damaged, but its variation in anatomical location may negate that as measurements between individuals (or between tibiae of the same individual) are incomparable (Dove *et al.* 2015). Hrdlička's tibial shape types will be shown to be of some importance to this study in Chapter 7.



афанасьевской и карасукской культур

mur					Tibia						Humerus				Radius			Ulna		
10:9. Указатель платимерии	6. Передне-задний диаметр	6:7. Указатель пилястрии	8:2. Указатель прочности	(6+7):2. Указатель массивности	1. Длина	8а. Передне-задний диаметр	9а:8а. Указатель платикнемии	10в:1. Указатель прочности	12. Угол ретроверсии	13. Угол наклона	1. Длина	5. Наибольший диаметр сечения	6:5. Указатель сечения	7:1. Указатель прочности	1. Длина	4. Передне-задний диаметр	5:4. Указатель сечения	1. Длина	14. Передне-задний диаметр	13:14. Указатель платолении
89	38	123	20.7	13.6	396	45	62	21.7	10	6	363	28	64	19.3	274	18	72	306	30	80
74	38	119	20.0	14.2	420	40	70	21.0	13	10	345	27	74	20.0	265	16	87.5	290	28	82
85	33	114	20.4	13.0	379	39	61.5	21.9	10	5	328	25	80	18.6	244	18	67	264	27	93
68	31	91	20.7	13.9	380	41	56	22.1	10	6	329	—	—	21.0	—	—	—	268	28	89
76	34	113	20.0	13.2	402	39	69	20.1	11	8	352	25	76	19.6	—	—	—	285	30	77
70	29	91	20.8	13.5	390	36	80.5	20.2	14	12	326	26	77	21.8	—	—	—	278	29	86
76	34	100	22.6	14.7	395	38	79	22.8	18	11	331	25	84	21.4	253	18	83	277	31	77
67	29	97	—	12.1	401	37	67.5	—	—	—	347	22	77	—	—	—	—	—	—	—
75	34	113	22.4	14.3	376	33	79	21.3	10	4	316	21	81	19.6	248	15	87	272	25	80
78	36	113	20.0	13.2	435	47	64	21.4	6	2	—	—	—	—	—	—	—	—	—	—
76.5	29	104	19.8	13.1	365	38	63	21.4	—	—	310?	26	81	24.2	—	—	—	—	—	—
78	33	110	20.2	13.0	418	41	73	20.3	9	5	333	25	76	20.1	258	19	74	290	27	81.5
71	33	103	20.9	13.4	392	41	56	21.7	8	4	341	23	83	19.6	268	17	88	281	28	82
76	33	106	20.7	13.2	417	37	84	20.6	7	2	349	27	78	21.5	279?	20	75	30[illegible]	29	96.5
82.5	36	106	21.9	14.0	450	43	77	21.3	9	5	355	26	77	20.3	282	18	78	302	30	77
65	33	97	19.6	12.8	437	45	73	22.2	10	5	358	27	74	19.8	280	21	67	294	29	85
—	—	—	—	—	345	37	62	22.0	5	0	318	25	68	21.1	231	18	67	—	27	81.5
81	26	89	19.7	12.7	360	35	68.5	21.7	14	6	300	23	74	21.0	235	18	67	257	25	88
—	—	—	—	—	369	34	65	—	—	—	—	—	—	—	236	—	—	—	—	—
75	28	104	—	12.6	365	34	73.5	—	—	—	309	24	71	—	237	—	—	—	—	—
79	29	107	20.1	13.1	345	31	74	19.4	—	—	302	23	69.5	19.2	225	17	70.5	248	23	96
71	26	90	19.9	12.9	348	36	64	21.6	18	12	298	26	61.5	21.8	—	—	—	—	—	—
79	32	123	19.9	13.1	36[illegible]	36	64	21.3	—	—	312	23	83	21.[illegible]	—	—	—	271	24	81
100	31	115	19.1	12.3	358	33	79	20.7	12	7	—	—	—	—	—	—	—	—	—	—
79	32	103	19.0	12.6	418	37	57	17.9	—	—	—	—	—	—	—	—	—	—	—	—
78	30	100	19.1	12.3	396	33	76	19.4	9	5	—	—	—	—	—	—	—	—	—	—
84	32	100	20.3	13.0	386	39	90	19.4	2	1	345	27	78	21.7	260	20	65	275	30	83
79.5	30	100	19.3	12.7	380	35	68.5	18.9	4	0	329	22.5	78	19.7	259	17	76.5	278	26	85
68	25	93	19.7	12.8	340	30	70	20.0	18	10	300	23	74	20.0	—	—	—	—	24	79
60.5	26	104	17.7	11.6	362	29	79	18.5	10	9	320	23	69.5	19.1	—	—	—	—	—	—

23 Палеоантропология СССР

353

Figure 4.1.4 A list of cnemic indices for assemblages within the Soviet Union. This table shows individual anthropometrics of the Afanasyevskaya and Karasukskaya cultures, excavated in the 1920s-30s. Measurement 9a:8a is the cnemic index, among length, the diameters, and angle of retroversion. As taken from Debets (1948: 256).

4.2 Modern investigations

Current research attempts to disengage with the racial classifications of early 20th-century anthropologists and to focus on activity-based explanations of variations in tibial diaphyseal shape, seen in this project. While many of the researchers discussed above focussed on measuring and classifying, this study and others investigate how these measurements can be used to further scientific bioarchaeological research. As discussed in depth in Chapter 2, bone has the ability to remodel based on a number of forces experienced as a result of activity and local periosteal loads. This section will present research conducted since the 1980s, but will mostly focus on research since 2000, emphasising investigations that utilise a biomechanical approach to explore changes in cross-sectional geometry (CSG) and tibial shape with regard to activity as well as evolution.

The tibia has been studied from a biomechanical perspective more than any other human bone (Ruff and Hayes 1983b). The first biomechanical analysis of an ancient tibia was Endo and Kimura's (1970) study of the Neanderthal tibia from Amud, near Galilee. They noted that the Amud tibia has a prominent posterior margin (the posterior pilaster), identifying it as a Hrdlička Type IV or rhomboid. They calculated bending moment, section modulus, maximum height and second moments of area, and found these CSG values to be higher in Amud I than in other Neanderthal remains and modern Japanese individuals. However, Endo and Kimura argued that the strong bones of Amud I were due to strong repetitive muscle activity of the knee and ankle in the sagittal dimension. They also pointed out the difference in character and cross-section between Neanderthal types, ostensibly caused by variation in muscle strength – the Southwest Asians had a flatter cross-section and the Europeans rounder, shown in Figure 4.2.1.

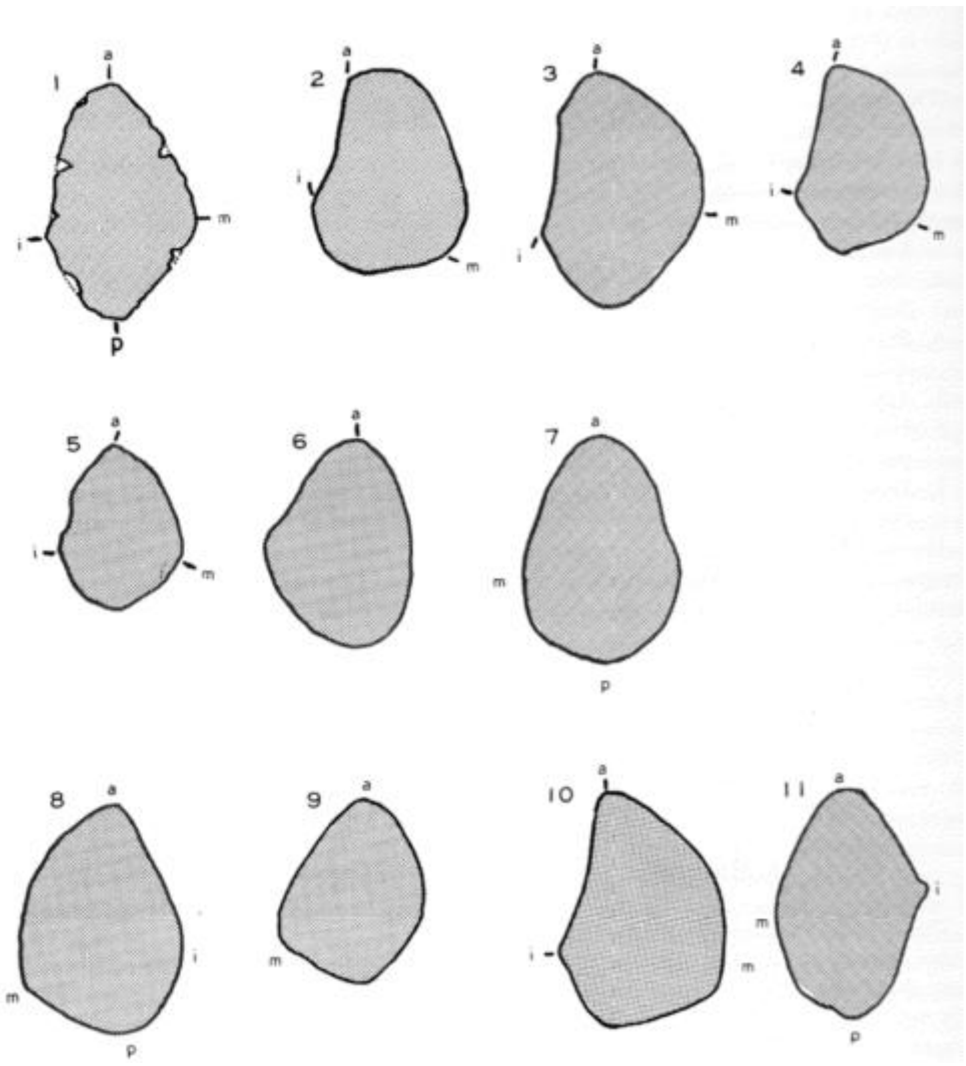


Figure 4.2.1 Periosteal outlines of tibial cross-sections at midshaft from Neanderthals. From upper left corner: **1** Amud I, **2** Skhul IV, **3** Skhul V, **4** Skhul VI, **5** Tabun I, **6** Spy II, **7** Kiik-Koba, **8** Solo A, **9** Solo B, **10** Grimaldi, **11** Obercassel. As taken from Endo and Kimura (1970: 348).

Lovejoy *et al.* (1976) were among the first wave of researchers to apply this biomechanical work to archaeological samples, investigating biomechanical explanations for platycnemia, an oft-researched issue as demonstrated in section 4.1. Of particular relevance – mentioned in Chapter 2.4.1 – is the posterior pilaster, a bony structure extending longitudinally down the posterior edge of the tibia. As the authors point out, removal of the posterior pilaster will not turn a platycneic tibia into a eurycnemic one, as a suite of changes have taken place to produce a flattened tibia. Also, when viewed in cross-section, it is difficult to determine where the pilaster begins and the posterior aspect of the tibia ends. The researchers compared five eurycnemic modern tibiae with five platycnemic archaeological ones at five points along the shaft, normalising for length. Using cross-sectional areas, they found that the amount of bone as a function of length did not differ between the groups, but bone strength (determined as resistance to stress in the second moment of area about the centroid) as a function of length was higher in the eurycnemic group (Lovejoy *et al.* 1976: 499). Despite having lower strength, the platycnemic group have similar geometric proportions, suggesting a redistribution of compact bone and increased anteroposterior strength at the expense of mediolateral strength (Lovejoy *et al.* 1976: 500). On the other hand, the platycnemic tibiae have higher torsional strength. The researchers conclude that platycnemia – as suggested but not proven by earlier work – is due to a specific loading pattern consisting of increased anteroposterior and torsional stress, particularly on uneven substrates (Lovejoy *et al.* 1976: 505). Lovejoy's illustration of platycnemic and eucnemic tibiae was shown as Figure 2.4.1.

Ruff and Hayes' (1983) study continued to examine archaeological tibial diaphyseal shape using biomechanics, investigating tibiae and femora from Pecos Pueblo, discussed briefly in Chapter 3.5. Using the SLICE software developed by Nagurka and Hayes (1980), cross-sectional geometry and moments of area were much easier to calculate, though the bones still needed to be sectioned in that era. SLICE digitally divided the cortical area into 1 mm trapezoids and calculates the CSG properties for each, combining them to determine the composite properties of the whole area (Ruff and Hayes 1983: 366). The study used bones from 119 young adults from the Pecos Pueblo site in New Mexico; tibial sections were taken at 20%, 35%, 50%, 65%, and 80% of the distance from the distal end. Results combined males and females, and CSGs examined are bone areas, second moments of area (bending rigidity), polar second moment of area (torsional rigidity), section moduli (maximum stress), and maximum shear. The purpose of the study was to examine points of stress and calculate these CSGs within each bone: as shown in Figure 4.2.2, the authors compared the areas of greatest bending rigidity as well as shape, although shape was not qualitatively compared as in Hrdlička's guide. They also explained why the second moment of area around the maximum and minimum axes (I_{max}/I_{min}) is crucial to understanding stress on long bones: it compares distribution of bone around a centroid, indicating the bone's resistance to bending and torsional loads (Ruff and Hayes 1983: 371). These two types of loads are more important for understanding bone's resistance to failure than axial or compressive load, as the bones of the lower limb are strongest in compression. By examining bone distribution, they could theoretically estimate the resistance to torsion and bending based on bone shape. Ruff and Hayes argue that the proximal tibia, with bone distributed as far from the neutral axis as possible, is suited to resisting bending; the distal tibia, with bone distributed radially about a centroid, is suited to resisting torsion. However, the circular shaft shape could also be produced by bending loads applied in two perpendicular planes, complicating the argument, but in-vivo studies prior to their work showed that bending stress is greatest at 30% distance from proximal and torsional stress is greatest at 70-80% distance from proximal, bolstering their claim (Ruff and Hayes 1983b; Minns *et al.* 1975). Their summary of previous research on stresses during gait is crucial mainly for conveying the multitude of forces acting on the tibia at different times during different activities – though jogging produces greater bending stress than walking on the midshaft, it produces less torsional stress, and bending moments change considerably throughout gait stances.

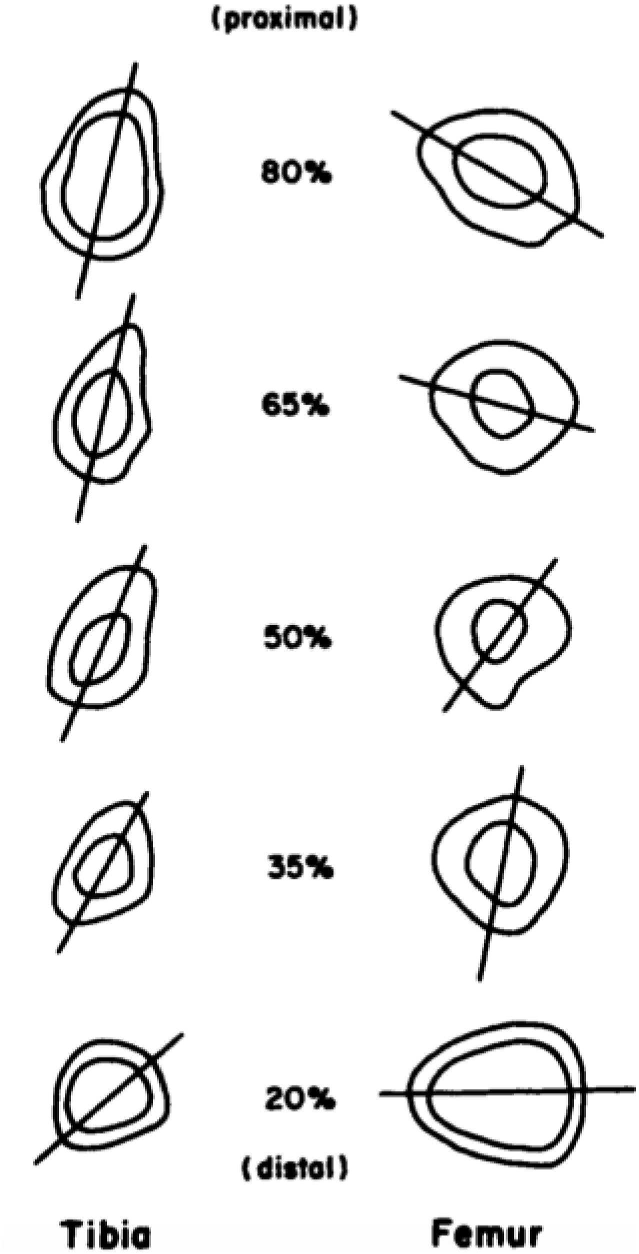


Figure 4.2.2 Diagram of tibial and femoral cross sections at various points along the shaft, with a line indicating the direction of greatest bending rigidity. As taken from Ruff and Hayes (1983: 370).

Ruff and Hayes' conclusions were presented in two segments: one more general and one specific to age, sex, and asymmetry. The major difference found between the Pecos Pueblo tibiae and the modern sample was the former's higher I_{max}/I_{min} ratio, also described in terms of cross-sectional shape: the former are platycnemic and the latter eurycnemic (Ruff and

Hayes 1983: 379). Sexual dimorphism in cortical area was found to be greatest in the midshaft tibia; sexual dimorphism in the I_{max}/I_{min} ratio was more complicated. Dimorphism was greater in I_{max} than in I_{min}, resulting in the males appearing more platycnemic.

Later studies have focused on single extant tibiae from well-known archaeological sites. Stringer *et al.* (1998) and Trinakus *et al.* (1999) examined the tibia from Boxgrove, a British Middle Pleistocene site from approximately 500,000 years BP. Discovered in 1993, the site contained only one human bone,[5] an adult tibia with a prominent posterior pilaster, shown in Figure 4.2.3. Visual analysis of the external morphology showed no evidence of a lateral concavity: the anterolateral side was convex, continuing to a rounded anterior crest; the interosseous crest was damaged but appeared to be smooth (Stringer *et al.* 1998: 527). The soleal line was prominent and rough, and the posterior pilaster extended for 90 mm. Compared to other tibiae from archaic *Homo* specimens, the Boxgrove tibia fit solidly as they all featured a rounded anterior crest, a convex anterolateral side, and a prominent pilaster, which the authors found to be absent in more recent (anatomically modern) human tibiae. An approximate length of 373 mm was calculated using least-squares regression from known-length Pleistocene and late Holocene tibiae; that estimate is "relatively, but not exceptionally, high for an archaic *Homo* specimen" (Trinkaus *et al.* 1998: 536). Compared with the cnemic and midshaft indices of these samples, the Boxgrove tibia was smaller mediolaterally than archaic *Homo* and Neanderthals (cnemic index=68.4); the Boxgrove tibia's morphology and measurements led the researchers to identify it as belonging to *Homo heidelbergensis*.

---

[5] There were also two incisors. See Pettitt and White (2012).

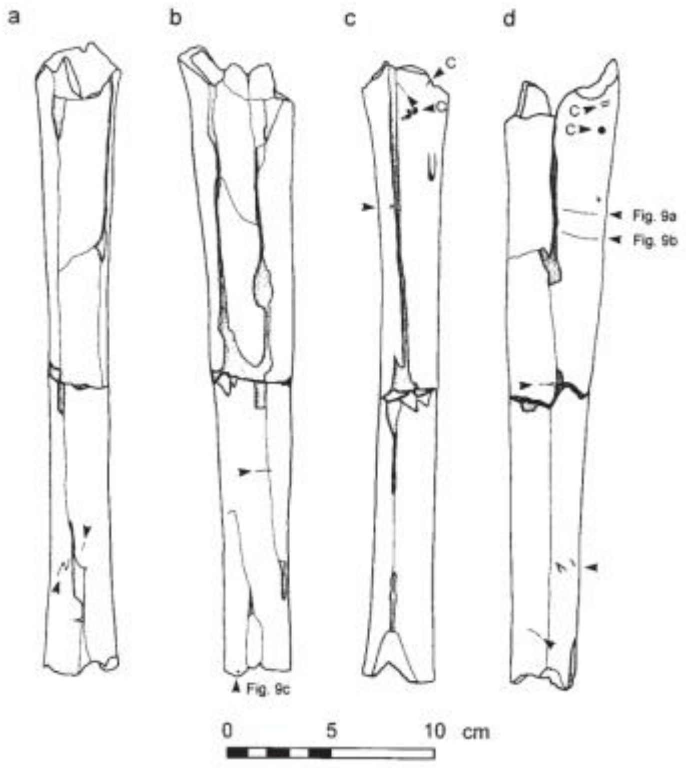


Figure 4.2.3 Drawings of the Boxgrove tibia from different angles showing carnivore gnawing. Note the posterior pilaster in **c** (posterior view). As taken from Stringer *et al.* (1998: 524).

Trinkaus *et al.* (1999) examined the Boxgrove tibia in sections for biomechanical analysis. CT scanning was used to image sections at five points on the shaft, including midshaft, using the least-square regression length estimation as both proximal and distal ends are missing. Cross-sectional geometric properties (discussed further in Chapter 7.5) of the tibia were compared to modern and archaic *Homo*, Neanderthal, and other tibiae, finding similarities to the modern human sample at 65% and 50% (note that the former includes the pilaster, shown in Figure 4.2.4). The Neanderthals were stronger mediolaterally than the Boxgrove and modern humans relative to anteroposterior strength (Trinkaus *et al.* 1999: 10). Although direct data for comparative specimens was not provided, I_{max}/I_{min} for the Boxgrove tibia was 2.04: this will be reviewed in Chapter 8 alongside the results from this study. Diaphyseal dimensions aligned this tibia with other late Pleistocene *Homo* and archaic and modern humans in that it was mediolaterally strengthened at midshaft, assumed to be due to activities with higher levels of either mediolateral loading or torsion.

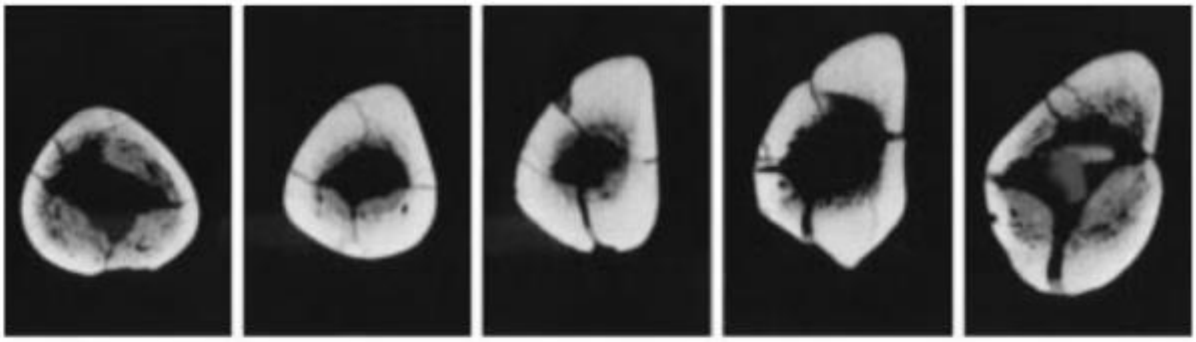


Figure 4.2.4 From left to right, CT scans of cross-sections of the Boxgrove tibia at approximately 20%, 35%, 50%, 65% (showing the pilaster), and 80% from the distal end, as taken from Trinkaus *et al.* (1999: 3).

Trinkaus *et al.* (2009) examined another single tibia from the site of Broken Hill, Kabwe, Zambia, discovered in 1921. Although a number of skeletal elements were found, Hrdlicka – one of the original anthropologists to examine the remains in 1930 – only associated the tibia to the cranium with confidence. The remains have been dated to the late Middle Pleistocene. The anterior crest was blunt and the lateral shaft lacked concavity, with a clear but minimal interosseous border (Trinkaus *et al.* 2009: 148), similar to other Pleistocene *Homo* tibiae; this was visible in the reconstructed sections in Figure 4.2.5. The authors pointed out that tibiae from this period tend to be less platycnemic than later samples and was similar to the Boxgrove tibia in that they are mediolaterally broad.

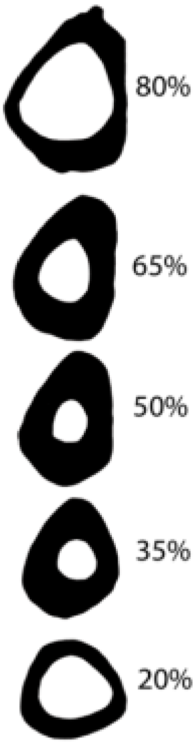


Figure 4.2.5 Reconstructions of the Broken Hill tibial diaphyseal cross sections at 20%, 35%, 50%, 65%, and 80% from the distal end. As taken from Trinkaus *et al.* (2009: 150).

In addition to paleoanthropological research, recent studies that have examined living humans have been able to discern tibial shaft shape and cross-sectional differences between athletes and controls. A study by Shaw and Stock (2009) addressed how much activity has an impact on bone change. The study assessed 15 field hockey players and 15 distance runners from current university teams alongside 20 non-athletic controls, all males between 19 and 30 years with no history of sports injury. Participants were given a questionnaire about their athletic history and then had both legs scanned by peripheral quantitative computed tomography (pQCT), which measures bone geometry, volumetric BMD, and stress-strain index by calculating second moments of area and polar moments of inertia in a specific limb (these properties will be discussed further in Chapter 7.5). The results of the questionnaire indicated that the runners began training competitively since about 13 years of age and the field hockey players since about 10; the runners had spent the time from age 12 until the time of study engaged in running or other load-bearing aerobic activities, while the hockey players were engaged in hockey or other anaerobic-intermittent activities (field sports). The pQCT scans showed that compared to the controls, the runners' tibias were "significantly stronger for virtually every measurement" (Shaw and Stock 2009: 153), including torsion and compression, total bone area, bending in the maximum and minimum planes, periosteal circumference, and average cortical thickness. The field hockey players were stronger than the controls on all counts but not as strong as the runners, but the difference in tibial shape - calculated as (maximum second moment of area / (body mass x length^2)) / (minimum second moment of area / (body mass x length^2)) – between the two was negligible. The greatest difference between runners and controls was in average cortical thickness, which was 11.8% greater in runners. The authors included a single midshaft scan of one individual from each category (Figure 4.2.6):

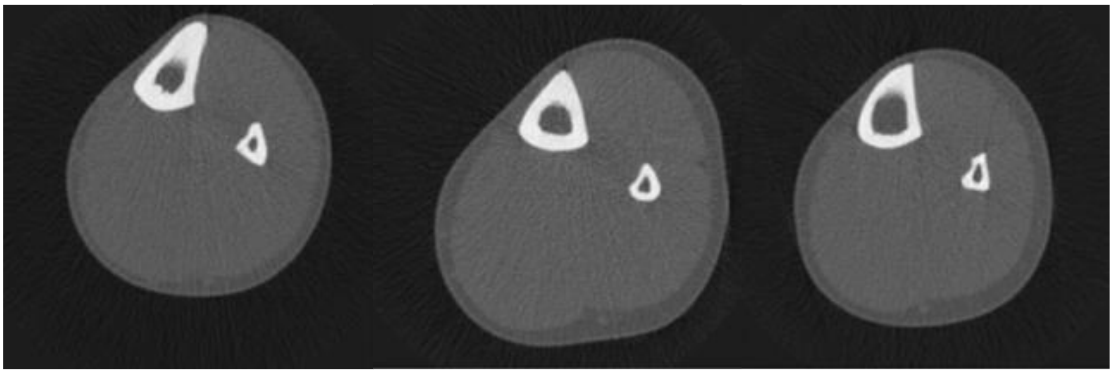


Figure 4.2.6 pQCT scans of tibial midshaft of a runner (left), control (centre), and hockey player (right). As taken from Shaw and Stock (2009:155).

Note the differences in shaft shape, with the runners displaying an isosceles triangle shaft with "increased maximum plane rigidity" while the hockey players have a more equilateral triangle shaft with equal rigidity in the maximum and minimum planes. Additionally, it is easy to see the cortical thickening in both groups of athletes compared to the controls.

A similar study conducted by Nikander *et al.* (2008) comparing male slalom and mogul skiers on the Finnish World Cup ski team to "normally active controls". Both groups had skied competitively for about 15 years, practiced more than 15 hours per week, and did weight training in addition to skiing. Slalom skiing involves quick directional changes along a steep slope without high impact landings; mogul skiing involves quick but straight downhill skiing on a very bumpy slope, with odd-impact landings. Common to both is the flexed skiing position with bent hips and knees, so the study investigated bone growth and strength on the femoral neck and tibial shaft using pQCT and MRI. They found that the slalom skiers' midshaft tibial BMC was 18% higher than control and that distal tibial BMC was 39% higher. The skiers' tibial midshafts were 10-15% larger in cross-section and 13-15% thicker than control (and 63-82% thicker at the distal tibial), but cortical density was the same (Nikander *et al.* 2008: 148). As a consequence of this, the skiers had considerably more mechanical rigidity – up to 61% higher than control at the slalom skiers' distal tibia. There were slight differences in tibial shape between the groups, but the authors did not remark on them outside of the pQCT scan shown in Figure 4.2.7.

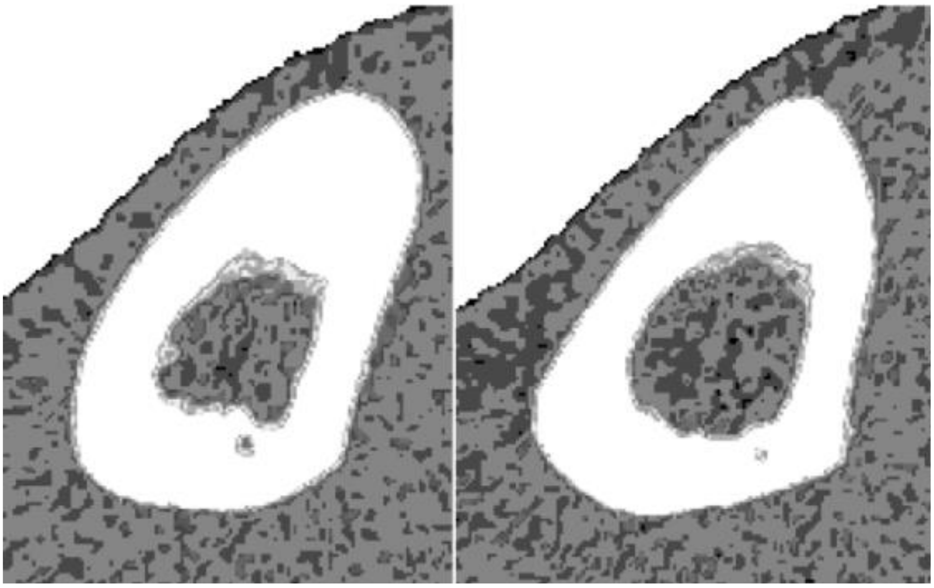


Figure 4.2.7 pQCT scan of tibial midshafts of a mogul skier (left) and a slalom skier (right). As taken from Nikander *et al.* (2008:149).

An additional study by Nikander *et al.* (2010) examined 204 athletes practicing a variety of sports, divided into groups of high-impact loading (volleyball, hurdling, and triple jump), odd-impact loading (soccer, racket games), high-magnitude loading (power lifting), repetitive low-impact loading (long-distance running), and repetitive non-impact loading (swimming). The athletes' history of practice was taken by self-reported questionnaires covering the previous five years, and BMC and cross-sectional geometry were obtained using pQCT scans. At midshaft, the mean BMC of the high-impact and odd-impact groups was 28-44% greater than controls (using reference data); the mean BMC of the high-magnitude group was 28% less than the controls, and the mean BMC of the low- and non-impact group was similar to the controls (Nikander *et al.* 2010: 1689). Total area, controlled for body size, was higher than control for all groups, and was highest in the high-impact group at 530 mm^2. The researchers reconstructed approximate tibial sections using average endosteal and periosteal radii from the centre of mass, shown in Figure 4.2.8, indicating that the exercise loading groups have increased periosteal area compared with the controls (Nikander *et al.* 2010: 1692). The study did not take into account the age of the athletes or variation in training – for instance, racket sport, volleyball, and soccer players often run as part of their training, which could be conflating the high-impact, odd-impact, and repetitive low-impact groups. While not contributing to an understanding of tibial midshaft shape change, the study still shows that varying athletic practices influence BMC and cross-sectional geometric properties depending on ground impact.

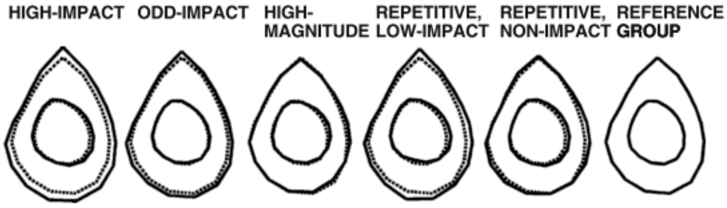


Figure 4.2.8 Reconstructions of average tibial cross-sections from each of the athletic groups and the reference group (far right). The reference group is shown as a dotted line overlaid on the exercise loading groups to indicate the increased periosteal area. As taken from Nikander *et al.* (2010: 1692).

The human tibia has been examined in bioarchaeological and biomechanical contexts for over a century. Tibiae have been used to further arguments about species identification in the fossil record, interpret activity of ancient *Homo* species, track changes in human activity in archaeological periods, and examine bone changes in response to sports practices. As it is the primary weight-bearing bone of the lower leg and is aligned with the principal vertical axis of the body, the tibia is particularly useful for assessing load-bearing activity. However, it is critical to note that these activity assessments must be comparative, and ideally utilise many individuals: the fossil tibia from Boxgrove, for example, cannot be used to imply that all members of late Pleistocene *Homo* species had high levels of torsion, as it represents only one individual. It is also necessary to highlight that an individual bone only represents the activity performed at time of death and, depending on the age of the individual, the bone may have been in a process of transition depending on that individual's activity level determined by several social factors, discussed in Chapter 3. Studies of modern athletes and controls can assist archaeological researchers by suggesting which activities result in certain tibial cross-sectional geometric properties and cross-sectional shapes, and particularly revealing that many types of activities can result in similar midshaft shapes and geometric properties. The importance of the tibia in examining ancient activity and movement is the basis for this study. The next chapter outlines the research questions based on the information presented in Chapters 2-4, covering anatomy of the lower leg, biomechanics, and defining activity in archaeological contexts.

5 Research Objectives and Hypotheses

The previous chapters have addressed the background of tibial anatomy, including the importance of examining the for research into mobility and ancient activity patterns, the relevance of the types of analysis that will be used within bioarchaeological contexts, and potential problems with these analyses, including the role of hormones in bone development and the lack of accounting for various types of activity in historical investigations. From the research presented, it is possible to draw the following conclusions:

- Bone shape in general and tibial shape in particular changes based on load-bearing activity type and intensity. Examples from living athletes demonstrate that age, sex, and type of activity play a role in changing diaphyseal shape.
- Individuals practicing different activities in ancient societies can be distinguished by a number of bone adaptations, including diaphyseal shape, asymmetry, and pathological changes.

The study utilises two methods, cross-sectional geometry and geometric morphometrics, to examine the tibiae from three Sudanese sites, discussed further in Chapter 6.

5.1 Research objectives

This study investigates the following objectives in a Sudanese archaeological context.

Activity patterns. Research has found that long bone cross-sectional diaphyseal shape is dependent on load-bearing activity (Shaw and Stock 2009; Nikander *et al.* 2008; Macintosh *et al.* 2014; Trinkaus and Ruff 2012; Ruff *et al.* 1984). Many bioarchaeological investigations, especially those that use small sample sizes, try to assign activities to human remains that are more speculative than scientific; examples include pushing off canoes (Wanner *et al.* 2007) and wrestling (Carroll 1988), both of which underestimate the amount of activity necessary to cause a change in bone shape. The purpose of this objective is to find trends that can isolate or associate population sectors, not tie them to particular activities.

- Does tibial midshaft shape vary within the examined assemblages, between and within estimated sexes, between different estimated ages of adults?
- Can the different assemblages consistently be separated by midshaft tibia shape? If so, is there a typical shape for each?

Subsistence strategy. The three Sudanese sites examined in this study, discussed further in Chapter 6, most likely practiced different subsistence strategies and had differing levels of nomadism. For the large mortuary population at Jebel Moya, mostly from the Meroitic period, it has been hypothesised based upon dental wear, pathology, and ceramics that this is a pastoral community (MacDonald 1999; Brass 2015). To what extent can this be supported or contested with tibial diaphyseal shape data? Burial patterns, ceramics, and botanical remains identify that 3-J-18 and Gabati practiced sedentary agriculture (Edwards 1998; Ginns 2010b).

- Do assemblages from sites with similar subsistence strategies have more similar midshaft tibia shapes than those with dissimilar strategies?

Methods. This study uses both cross-sectional geometry and geometric morphometrics to investigate tibial diaphyseal shape in cross-section.

- Do cross-sectional and morphometric approaches yield similar patterns of variation, similarity and difference?

Overall. What can be gained from using tibial midshaft shape and cross-sectional geometry to analyse activity within archaeological skeletal assemblages?

- Can tibial diaphyseal shape be used to infer past activity patterns in ancient societies?
- What insights can be gained into activity over the course of Sudanese history and prehistory from biomechanical and morphometric examinations of the tibia?

5.2 Hypotheses

Based on the research questions presented above, hypotheses have been developed. These will be directly addressed in Chapter 9 (Discussion).

Activity patterns

- Differences will be able to be seen between sex categories. Given that there are very few older adults in the assemblages, differences will not be seen between age categories with the exception of soleal line robusticity, which tends to increase with age.
- It is predicted that tibial shapes alone will not be evidence enough to make assumptions about archaeological assemblages. Like other scientific archaeological techniques, it is only an additional tool in the bioarchaeological arsenal, used to support an argument.
- Although the tibial shape makeup of a certain group may differ from others, this type of analysis lends itself to larger sample sizes and thus should be used comparatively; that is, it can only show differences in relation to another assemblage or group within an assemblage. The data can show that one group or one individual in a group was “more mobile” than another, but will be unable to make conclusions about single individuals.
- Additionally, the study will not be able to identify unique activities that have shaped the tibiae (for instance, ploughing or herding), but rather local or long-range mobility. As the tibia is shaped by both biomechanical forces acting on it during motion and associated muscle forces, no one activity is unique enough to always be correlated with a specific shape.

Subsistence strategy

- It is predicted that the percentage of diaphyseal shape categories will differ between the nomadic-pastoral group and the sedentary-agricultural groups, and that the nomadic-pastoral group will have a higher proportion of the tibial shapes associated with anteroposterior loading and that the sedentary-agricultural groups will have a greater diversity of shapes.

- The nomadic-pastoral group will be overall more robust, indicated by higher cross-sectional geometric properties associated with increased anteroposterior bending strength and torsional strength.
- As these groups were chosen to be representative of their subsistence strategy rather than exceptions or outliers, the study will be able to draw conclusions about how sedentary agriculture and nomadic pastoral practices reveal themselves in tibial shape, which could be expanded to other Nilotic cultures and time periods.

Methods

- It is predicted that while cross-sectional geometric properties and geometric morphometrics individually answer different questions – strength vs shape – when combined they will reveal more specifically how strength and shape are related.

These hypotheses will be tested and the results will be shown in Chapter 8.

Overall

- See Chapter 9 (Discussion) for the implications of the above.

5.3 Summary of original contributions

The original contributions of this research, fitting the above questions, will benefit both the fields of biomechanics and Sudanese archaeology.

Besides Davies' examination of selected human remains from the Meroitic site of Gabati (2012) and Nikita *et al.*'s (2011) study of Garamantian limb bones including Kerma remains, cross-sectional geometric analysis of Sudanese remains has not been attempted in the past. It will be unique in the field of Sudanese archaeology, particularly in its attempt to explain assemblage differences in terms of subsistence activity, and the first to compare tibial diaphyseal shape to cross-sectional geometry. Discussed in Chapter 2, the tibia is uniquely responsive to activity performed during adolescence, and thus indicative of the work performed by peripubertal individuals in ancient societies. By measuring differences in tibial shaft shape and comparing them to known methods of dental analysis, it is predictably possibly to correlate certain tibial shapes to subsistence strategies. Reconstructing and comparing ancient patterns of activity has been a popular topic in the last decade, particularly for prehistoric periods. Unlike previous work in the field, this study takes a wide scope by examining material from several regions within Sudan with the aim of identifying a new method to determine subsistence strategy. Using new methods, this study applies the techniques developed by other researchers to the extensive collection of Sudanese human remains curated in the UK. Many questions in bone research remain unanswered; the aim of this study is to contribute to the field's understanding of the link between biomechanics, bone building, and the reconstruction of ancient activity patterns and subsistence strategies. The following chapters cover the materials used, including a brief background of archaeological research in Sudan regarding the time period under investigation, and the methods used to test the hypotheses.

6 Materials

This chapter will cover the materials used. The backgrounds of the three Sudanese sites (Jebel Moya, Gabati, and 3-J-18), the Egyptian site used in the pilot study, and the outgroup site of Chichester are discussed along with previous relevant research conducted on the human skeletal remains. There has been considerably more research conducted on the Jebel Moya material as it was excavated longer ago than the other sites.

6.1 Site selection

The purpose of this project is to investigate the differences between Sudanese groups with varied subsistence practices based on the shape and strength of the tibial diaphysis. The three sites were chosen on the basis of geographic and temporal proximity and strong archaeological arguments for their subsistence strategy. As will be discussed below, each site includes a selection of individuals from the mid-first millennium AD, approximately the time of the Meroitic to post-Meroitic periods. 3-J-18 and Gabati are in closer geographical proximity to each other and both represent societies based on agriculture, but appear to differ in economic status; Jebel Moya is further south but practiced seminomadic pastoralism. Naqada, the Egyptian site used in the pilot study, is predynastic Egyptian and agriculturally-based; it was chosen for an initial test of methods as representative of early agriculture, but lacks the sex and femoral head diameter necessary for further analysis. Chichester is a post-medieval coastal English site used for outgroup comparison. The purpose of its inclusion is to ensure that any differences seen between the Sudanese sites are not genetic, as similarity between tibial shapes in Sudan and England is most likely due to activity rather than genetic similarity.

6.2 Sudanese archaeology and time periods

The time frames covered by these sites are within the Meroitic and Medieval/Christian periods, defined by Welsby Sjöström (2001) and Thomas (2008) based on pottery analysis and shown in Table 6.2.1 and a map of Sudanese archaeological sites is in Figure 6.2.2.

Early Meroitic	3rd to1st century BC
Classic Meroitic	1st to 2nd century AD
Late Meroitic	Late 2nd to mid 4th century AD
Early Post-Meroitic	Mid 4th to late 5th century AD
Late Post-Meroitic	Late 5th to mid 6th century AD
Transitional Christian	Mid to late 6th century AD
Early Christian	Early 7th to mid 9th century AD
Classic Christian	Mid 9th to mid 11th century AD
Post Classic	Mid 11th to mid 13th century AD
Late Christian	Early 13th to mid 14th century AD
Terminal Christian	Mid 14th to late 15th century AD

Table 6.2.1 Time periods in Sudan, after Thomas (2008) and Welsby Sjöström (2001).

Figure 6.2.2 (next page) Map of Sudan showing archaeological sites (red triangles) and modern towns (maroon circles) with the study sites highlighted. Courtesy Derek Welsby and the Sudan Archaeological Research Society.


ASWAN
1st cataract
Egypt
RED SEA
Wadi el-Allaqi
Wadi Halfa
2nd cataract
Lower Nubia
Batn el-Hajar
Akasha
Amara West
Sedeinga
Jebel Dosha
Tinare
Wadi Gabgaba
Jawgul
3rd cataract
Kerma
Sudan
Upper Nubia
Nile
ABU HAMED
El-Ga'ab
Basin
Kawa
3-J-18
Sudan Military
Railway
KAREIMA
4th cataract
Fifth
Cataract
el-Kurru
Dongola Reach
Napata
Usli
Dangeil
Berber
ED-DEBBA
Gala
Abu Ahmed
Wadi Howar
ATBARA
Gabati
es-Sour
Atbara
el-Metemma
Meroe
Wadi Muqaddam
Shendi Reach
Wadi el-Melik
6th cataract
Butana
OMDURMAN
KHARTOUM
KASSALA
Eritrea
Blue Nile
MODERN TOWNS
Ancient sites
Atbara/Setiet
WAD MEDANI
White Nile
GEDAREF
Jebel Moya
KOSTI
SENNAR
N
Ethiopia
South
Sudan
0
250 km

6.2.1 History and archaeological research in the region

The following section presents a brief introduction to Sudanese history from the Kerma period, shortly before the period of study presented here, to medieval. Note below that the introduction and spread of Christianity may not have been immediate, as shown by the Mis Island (3-J-18) cemetery's adoption of Christian burial patterns. While the Jebel Moya cemetery covers these periods, there is no evidence of their interaction with the Meroitic sphere of influence, so the nomenclature of the time period is not an exact match. Also note that the name "Nubia" specifically refers to the area that in antiquity was demarcated as below the first Nile cataract and does not include Jebel Moya.

The region between the first and second cataracts is Lower (or Egyptian) Nubia, and further south is Upper Nubia. Upper Nubia was the gateway to sub-Saharan Africa for the Egyptians, through which they could trade Mediterranean products for African luxury goods such as animal hides, elephant and hippopotamus ivory, and gold (Bianchi 2004; Edwards 2004). Around 2500 BC, three cultures arose from the Neolithic: the Pan-Grave Group, the C-Group, and Kerma; Egypt's first recorded trade with Nubia occurs around this time. Jebel Moya, situated in the White Nile-Blue Nile triangle, is technically not within Nubia, thus this study refers to all the samples as representative of the "Sudanese" landscape rather than the Nubian.

The Kerma period, from 2400-750 BC (Edwards 2007), ended with a series of Egyptian invasions and the subsequent collapse of Egypt's New Kingdom, leading to the rise of the Kingdom of Kush, centered at Napata between the third and fourth cataracts; the Napatan period is generally considered to be from around 750 BC-350 BC (Fuller 2013). Beginning in the eighth century BC, the Napatan kings were able to establish rule in Egypt as the XXVth dynasty for the next 200 years until the Assyrian invasion (Shinnie 1996; Kirwan 2002). After three centuries, Kush controlled the entire Upper Nile south of Khartoum as well as the Lower Nile and part of the Levant, allowing Nubia to trade freely with the Mediterranean. There was also considerable building activity in the Dongola Reach, at Kawa, Jebel Barkal, and Sai Island, and burials from this period are "Egyptianised", sometimes featuring mudbrick pyramids (Kirwan 2002; Edwards 2004). Evidence of agriculture at Kawa, examined by Fuller (2004), showed mostly Pharaonic winter crops such as emmer wheat and barley as well as lentils and grass peas, all of which had probably been in the area since the late Neolithic; millet remains could have been for animal feed as well as for human consumption. There were also seeds of fruit crops and wild fruits (Fuller 2004). It should be noted that most excavations focusing on the post-Kerma periods have been biased towards tombs and monumental architecture (Fuller 2013), thus data from settlements and particularly botanical and zoological data are slim.

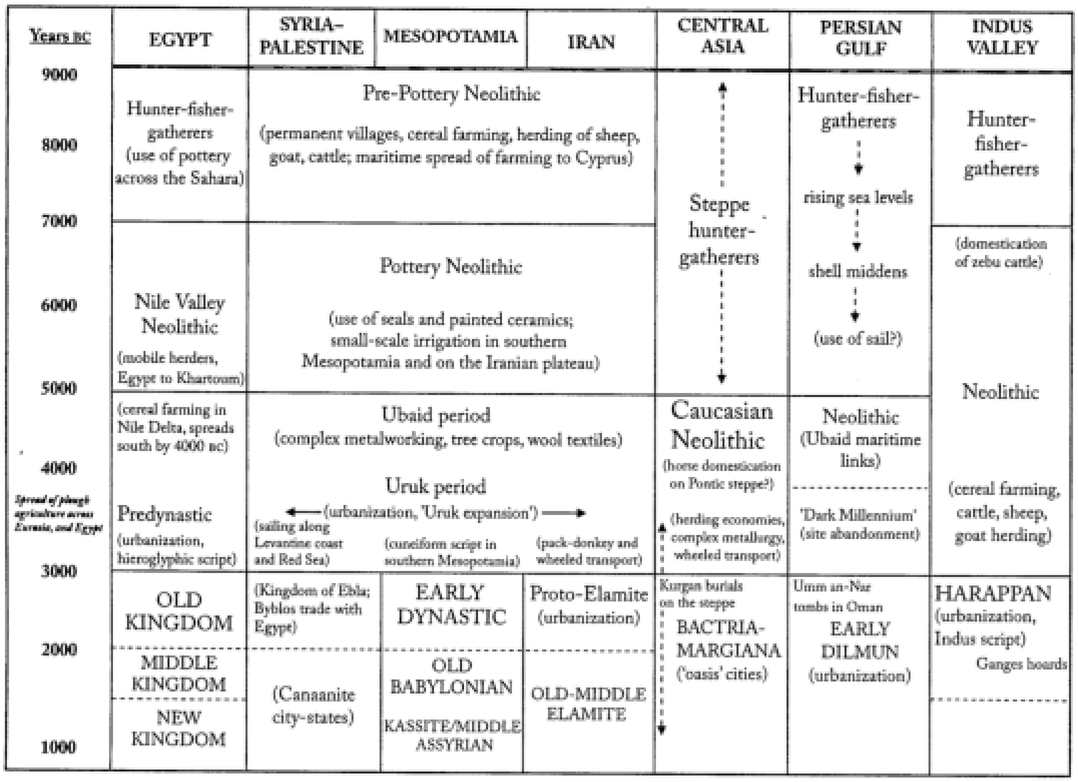
In the third century BC, the capital was moved for unknown reasons to Meroë, in the area between the fifth and sixth cataracts known as the Shendi Reach, beginning the Meroitic period (Shinnie 1996; Edwards 2004). It is situated near the first tributary below the merging of the White and Blue Niles, making it ideal for trade; it also is near local sources of iron (Edwards 2004). Although Meroë had a written language, it remains poorly understood and mostly unpublished, so historical records from this period are from the Greeks and later Romans (Edwards 2004). The city has a number of heavy masonry stone-walled compounds including a palace and government buildings, small frescoed temples, and a Roman-style bath. Nearby are about forty Meroitic pyramids, with the royal bodies interred in wooden coffins with luxury goods and evidence of retainer and animal sacrifice (Kendall 1997; Edwards 2004). This period saw the rise of a corps of cultural elites and differentiation of regional and local cultures, which can be seen in the numerous Meroitic-inspired local pottery traditions as well as differing types of burial styles (Edwards 2004). New sites, thought to be farmsteads or small villages, were built inland from the east bank of the Nile, relying on wells and wadis for cultivation. This movement into differing environmental zones implies new emphases in primary economic production: these populations had a system of *shitwi* winter crops and *seifi/dameira* summer crops (sorghum and beans), suggesting they were mostly or entirely dependent on agriculture (Fuller 2004; White *et al.* 2004; Fuller 2013), differentiating them from the earlier Kerman reliance on cattle. Fuller (2004) argues that sorghum, probably the central cereal crop of the Meroitic era, may have been used for beer brewing and gained symbolic importance, which could explain its depiction in art. Cotton was also being cultivated for a local textile industry, with evidence at Qasr Ibrim and Hamadab. These new agricultural settlements likely attracted individuals new to farming, particularly from the semi-desert regions which saw a decline in rainfall at this time (Fuller 2013). This could be a prime time to look for local variation in tibial shape as individuals shifted from light to intensive agriculture or immigrated from different regions.

The population of the city of Meroë declined around 350 AD, when the Axumite kings from Ethiopia claimed sovereignty (Edwards 2004; Edwards 2007). The Romans withdrawing from Upper Egypt at the turn of the fourth century AD had added additional unrest to the region. Key questions centre around the relationship between the city of Meroë and peripheral peoples (Shinnie 1996; Kirwan 2002; Edwards 2004). Despite being situated in the city's sphere of influence, the Jebel Moya pottery assemblage does not include any remains of Meroitic pottery and, as argued below, maintained a pastoral economy rather than agricultural (Brass and Schwenniger 2013). Research showing substantial consumption of sheep/goats and cattle at Meroë indicated some relationship with pastoralism (Clutton-Brock 2000; Chaix 2011), although whether through trading with nomadic pastoralist groups in the Dongola Reach or Western Butana, which was the northernmost savannah region and thus experienced a different climate and rainfall, or herding by citizens of Meroë is unknown.

The end of the Meroitic kingdom marked a shift away from trade of luxury goods and wheel-made pottery, although Edwards was keen to argue that this is not the dark age described by many previous authors (2004). There seemed to be a variety of new pottery traditions developing in both Upper and Lower Nubia and cultural continuity among the elites. Burials shifted away from pyramids and Egyptian-style coffins back to stone-covered tumuli (Shinnie 1996). Around the fourth century, the *saqia* water wheel began to appear, allowing year-round cultivation of both temperate and tropical crops (Nielsen 1973; Soler 2012); new crops imported from sub-Saharan regions included pearl millet, cowpeas, and hyacinth beans, and isotopic data reveals an increase in consumption of these C4 plants in this period (Fuller 2013). From the sixth century, Christianity began to appear throughout Nubia, beginning the Nubian medieval period (Shinnie 1996; Edwards 2004). This is evidenced not only by an increase in Christian symbolism on artifacts but also in a lack of grave goods and burial in a supine position oriented east-west, and occasional group tombs possibly from monastic contexts (Zurawski 2005; Soler 2012). There does seem to have been a transitional period from the late 400s to 600s AD with mixed-type burials and features such as tumuli over otherwise Christian graves (Edwards 2001); additionally, a tattoo representing St Michael, the patron saint of Nubia, was recently found on a medieval mummy (Daniel Antoine, *pers. comm.*). Strong cultivation continued despite possible climatic fluctuations impacting the Nile floods in the ninth to eleventh centuries AD, with land ownership by individuals and the church first recorded at Qasr Ibrim. The crops introduced in the Meroitic period increased, and free-threshing wheat and viticulture were introduced (Fuller and Edwards 2001). Questions regarding this time period centre on Christian Nubia's relationship with Muslim Egypt and the rest of the Islamic world. For the first time, both Egypt and Nubia kept documents detailing their victory over the other, often with differing accounts of the same treaties (Edwards 2001; Edwards 2004).

6.2.2 Archaeological evidence for subsistence activity in Sudan

When assessing an assemblage as a whole, researchers can draw conclusions about subsistence strategy from a number of types of evidence. Botanical and faunal remains are utilised, as are vessels and building types. Indications that agriculture is older than expected are hotly contested; evidence of agriculture in the Middle East dates from the pre-pottery Neolithic, or 11000-9000 years BP (Wengrow 2010), shown in Figure 6.2.3. The same time saw pottery across the Sahara, but societies appeared to rely solely on foraging (Edwards 2004). The Nile Valley Neolithic is said to begin around 9000 BP, with herding practiced as far south as modern Khartoum. Timelines for grain cultivation in Sudan differ between grain types, with millet and sorghum domesticated first before the introduction of wheat (Fuller and Edwards 2001; Fuller 2004); evidence of millet processing dates to the early Holocene in Egypt and Libya, and is particularly well-suited to an arid environment, which the Sahara region experienced in the mid- to late Holocene (Butzer 1975; Fuller 2004). The earliest domesticated millet seen in Sudan, at Ukma, is an Asian imported species, supporting the argument that agriculture was imported from the Near East (Butzer 1975). Sorghum is first seen at the beginning of the first millennium BC at Kawa (Fuller 2004). The earliest grinding stones in Sudan are from the Mesolithic (9500 BP), at which point domesticated cereals have not been discovered. This complicates the issue of the agricultural transition: grinding stones were used on wild grasses for an extended period of time before domestication by foraging groups, Asian domesticates were utilised before African cereals were domesticated, and individuals continued to practice foraging well into the Meroitic period, seen at Jebel Moya (Wendorf and Said 1967; Brass 2009; Brass and Schwenniger 2013). Haaland (1997) argued that the adoption of grinding stones and pottery shortly after encouraged the move towards sedentism, but this is also an oversimplification. Sudan has had groups that rely on a combination of foraging and pastoralism throughout its history and prehistory, most recently documented by Bradley in 1992. The traditional archaeological view of plant and animal domestication leading humans towards sedentary agriculture ignores the variety of human activities related to resource acquisition.



Years bc	EGYPT	SYRIA–PALESTINE	MESOPOTAMIA	IRAN	CENTRAL ASIA	PERSIAN GULF	INDUS VALLEY
9000 8000	Hunter-fisher-gatherers (use of pottery across the Sahara)	Pre-Pottery Neolithic (permanent villages, cereal farming, herding of sheep, goat, cattle; maritime spread of farming to Cyprus)			Steppe hunter-gatherers	Hunter-fisher-gatherers rising sea levels shell middens (use of sail?)	Hunter-fisher-gatherers
7000 6000	Nile Valley Neolithic (mobile herders, Egypt to Khartoum)	Pottery Neolithic (use of seals and painted ceramics; small-scale irrigation in southern Mesopotamia and on the Iranian plateau)					(domestication of zebu cattle) Neolithic (cereal farming, cattle, sheep, goat herding)
5000 4000 Spread of plough agriculture across Eurasia, and Egypt	(cereal farming in Nile Delta, spreads south by 4000 bc) Predynastic (urbanization, hieroglyphic script)	Ubaid period (complex metalworking, tree crops, wool textiles) Uruk period ←(urbanization, 'Uruk expansion')→ (sailing along Levantine coast and Red Sea)	(cuneiform script in southern Mesopotamia)	(pack-donkey and wheeled transport)	Caucasian Neolithic (horse domestication on Pontic steppe?) (herding economies, complex metallurgy, wheeled transport)	Neolithic (Ubaid maritime links) 'Dark Millennium' (site abandonment)	
3000	OLD KINGDOM	(Kingdom of Ebla; Byblos trade with Egypt)	EARLY DYNASTIC	Proto-Elamite (urbanization)	Kurgan burials on the steppe BACTRIA-MARGIANA ('oasis' cities)	Umm an-Nar tombs in Oman EARLY DILMUN (urbanization)	HARAPPAN (urbanization, Indus script) Ganges boards
2000 1000	MIDDLE KINGDOM NEW KINGDOM	(Canaanite city-states)	OLD BABYLONIAN KASSITE/MIDDLE ASSYRIAN	OLD-MIDDLE ELAMITE			

Figure 6.2.3 Timeline of major subsistence practices from Egypt to the Indus (Wengrow 2010: xii).

Caprines and bovines have a very different domestication history from crops. Domesticated ovicaprine and bovine remains have been found in Arabia from 8000 BP and ovicaprines in southern Africa at 6000 BP, indicating a slow movement southwards (Sadr 2008;

McCorriston *et al.* 2012); wild *Bos primigenius* had been hunted since the Middle Paleolithic. There is genetic evidence for independent cattle domestication in North Africa, but the time it reached Egypt is unclear. Comparisons of the size of faunal remains at various sites show a reduction in size by the Early Neolithic, but these still fall within wild *Bos* ranges, and as Brass (2001) argued, by definition the Neolithic is linked to animal and plant domestication and thus whether these are wild or domestic *Bos* affects whether the site can be called Neolithic. An additional line of evidence is a lack of aquatic vertebrates at certain sites, which along with environmental data indicates an environment too arid to support wild *Bos* without human assistance. Predynastic Egyptian rock art depicts cattle with artificially deformed horns, and the Old Kingdom sites of Badari, Hammamiya, Hierakonpolis, and Qau feature elaborate burials of *Bos* remains, some with linen coverings and grave goods, indicative of cattle worship (Trigger 1983). Brass associated the fusion of pastoral culture and agriculture with evolving religious associations between the cow goddess Hathor and the king (Trigger 1983; Brass 2001; Brass 2013).

Figure 6.2.4 Cattle bucrania at Kerma. Courtesy Archaeometria Modszertran Elmelet (2013).

In Sudan, cattle were of great social and ritual importance, with bucrania[6] adorning numerous burials from the Kerma period beginning around 5500 BP (see Figure 6.2.4) The key site of Kerma features a royal burial tumulus with 400 sacrificed persons surrounded by thousands of bucrania. Among all domesticate faunal remains from the Ancient Kerma period, cattle dominate all assemblages. Although the town of Kerma was quite large, there is disagreement over whether the surrounding area at the time was moist enough to support such a large cattle population or whether they were herded over the Sahel and brought to Kerma as trade and tribute (Thompson *et al.* 2008). Although the faunal remains mostly comprised domestic cattle, sheep, goats, and dogs, remains of wild species were also found, including hippopotami, turtles, crocodiles, giraffes, gazelles, and elephants (Chaix and Grant 1993; Chaix 2011). There were also remains of Nile perch, tilapia, and catfish. Even in a culture that clearly placed a high value on cattle – as Blench and MacDonald (2006) argued, Kerma belongs in the oeuvre of trans-Sahelian cattle cults as well as in the Nile sphere of influence – there were significant dietary contributions from hunting and fishing (Thompson *et al.* 2008: 378). The Egyptians regarded the Nubians as great hunters, although it is possible they were continuing traditions that had died out in Egypt due to climatic change: increasing aridity could no longer support large populations of wild herbivores (Butzer 1975). It is unknown whether these wild game and fish were collected primarily for diet or for status. Further, peripheral communities within the Kerma kingdom – particularly if they were key or supplemental contributors of cattle – were possibly more pastoral or practiced a mix of pastoral-agriculture (Brass 2014). Thus broad statements like “Kerma was an agricultural empire” are false as a number of subsistence strategies supplement a functioning primarily agricultural society including gathering of wild grasses (Harlan 1989). The presence of so many cattle indicates that Kerma was likely agropastoral, in line with the numerous trans-Sahelian cattle cultures, discussed by KC MacDonald (*pers. comm.*). It should be noted that many medicinal plants throughout history, though not necessarily in the Sudanese case, have always been wild and required expert foraging (Dahab 1995).

---

[6] Cattle skulls with horns

It is important to point out the extent of the environmental factors that influence subsistence strategies in Sudan. There is a significant difference in rainfall between northern Sudan and the region south of Khartoum, affecting the soil quality and resulting in differing crop and grassland habitats, shown in Figure 6.2.5. The region north of the 4th Nile cataract is hyperarid, receiving 0 inches of rain, with irrigation-based agriculture only possible along a narrow region adjacent to the Nile, with no areas further out for grazing (Tothill 1948). The major crops grown here in the Meroitic period were wheat and barley, ideal for irrigated areas (Fuller and Edwards 2001). In the Atbara region, there can be 12-20 inches of rainfall per annum over a period of 4-5 months (Tothill 1948: 33; Van Noordewijk 1984), allowing for adequate grassland for grazing and limited sorghum agriculture (Fuller 2013), although the grassy areas require travel on the part of the herders. This difference in rainfall and plant density affected the type of subsistence practiced by individuals and groups in these regions, and may have had an impact on amount of distance traveled to farm, herd, or gather.

Figure 6.2.5 Map of Sudan showing vegetation in different regions as influenced by rainfall. Note that the areas examined in this study are in the northernmost "desert" region and the "acacia short grass scrub" region. As taken from Tothill (1948: 34).

Bioarchaeologically, studies by Stock *et al.* (2011) and Nikita *et al.* (2011) discussed in Chapter 3.5 distinguish between the more mobile groups (Jebel Moya and Jebel Sahaba) and the less mobile agricultural groups (Kerma and Garama) on the basis of femoral, tibial, and humeral rigidity and robusticity, indicating that biomechanics can be utilised towards this goal. However, archaeological evidence has more commonly been used to differentiate between nomads and sedentists (or the intermediate groups defined by Johnson, above) in the Sudanese archaeological record. As discussed by R.H. MacDonald (1999), taphonomic factors including re-use of sites, erosion, or multiple groups utilising the same region in different seasons make interpretation of population subsistence factors difficult. It is also important to recognize that behaviors and structures observed in ethnographies may not represent a one-to-one correlation with actual archaeological finds; ethnoarchaeology should be used to inform us of the possibilities of ancient behaviors rather than be treated as strict correlates (Lane 1994). Bradley's ethnography of a village in the Nile-Atbara region (1992) shows a clear difference in burial practices and quantity and type of household artifacts associated with the Kababish, a nomadic group, and the Kaja, a sedentary group. Bradley's hypothesis, that the sedentists would have more total artifacts and more varied artifacts, was proved correct (Sadr 1991).

Additionally, the nomads' rainy season camps differed in size and structure from the sedentary village, which was centered around a well; in the dry season the Kababish dug wells annually. Burial grounds operated by the sedentary Kaja are uniformly aligned and have clear markers of rank in the superstructures; the Kababish make every effort to return the dead to a central burial ground at a jebel, but there is little consistency of form and superstructure (Bradley 1992: 70). Due to Islamic customs, neither group uses grave goods apart from the superstructure, which are mostly brick for the Kaja and stone for the Kababish (Bradley 1992: 72). A conclusion one could draw from these cultures is that the cemetery of a sedentary society will be near a habitation site while that of a nomadic society might not be (Sadr 1991). The arrangement of the cemetery could be important – perhaps those cemeteries with less evenly distributed or more intercut graves belong to a nomadic group, burying deceased individuals seasonally with fewer visible reminders of where last season's graves were dug. The cemeteries at Kerma proper appear to be a good example of a stable urban agricultural population, with little intercutting at least during the *Kerma Classique* period (Edwards 2004). Comparisons with burials of mobile hunter-gatherer populations or strictly nomadic pastoralists are also useful for understanding differences in mortuary behavior (Wadley 1997; Papathanasiou 2011).

Certain problems arise when applying the complexity of a split village arrangement like those groups described by Bradley or Cribb (see Chapter 3.5) to the archaeological cemeteries under investigation (Lane 1994). First, grave goods present a problem as they are consistently present in the archaeological sites but not in the modern village. Perhaps a difference in quality or quantity could be observed, as seen in the Kadruka *Kerma Ancien* cemetery; these graves are noticeably poorer than those at Kerma proper in the same period (Sadr 1991). Second, what of the individuals who switch groups? A nomad marrying into a sedentary family after puberty, a situation described by Bradley (1992), will have the tibial structure of their original nomadic group. This question is best answered by looking at the cemetery group as an aggregate, producing an assemblage-wide answer; additionally, generational anomalies such as a short sojourn in a village to recover lost cattle should not overly affect results if the cemetery covers many hundreds of years. To examine origins within a group, other methods such as dental morphology to establish biological distance might be used, but the ethnographic studies cited above imply that the subsistence groups are genetically linked and thus the primary difference would lie in activity signatures; in some cases, ethnic identity and genetic relatedness are not linked (Collins 2004; Ali-Khan *et al.* 2011).

A key difference between nomadic and agricultural societies is number of members. Arguably, because agriculture requires sedentism (and vice versa) and can support a larger number of individuals, ancient urban settlements with multiple crops in rotation had fewer limits on size (Stock and Pinhasi 2011: 2). Nomadic societies require movement, particularly if they are pastoral and need to find additional fresh grazing land. Montane transhumant groups, for instance, do not move a considerable distance longitudinally but rather up and down mountains following seasonal growth of flora (Kelly 1995). Group size is limited by the amount of livestock on a given area of land. In a compact society, while individuals or sectors might have unique roles, it is likely that more people will participate in more types of labour (Lieverse *et al.* 2011; Macintosh *et al.* 2014); in a large agriculturally-developed urban area, individuals can develop skills into discrete professions.

Agricultural societies along the Nile Valley primarily relied on the river's annual inundation for watering crops. Egyptian and Sudanese agriculture relied on systems of mud brick irrigation canals that could be flooded and drained, with artistic evidence for this dating to the Scorpion King's macehead in the predynastic period (Butzer 1975: 21). From the Old Kingdom or possibly earlier, the tool for this was the *shaduf*, a first-order lever that lifted water in a single pot, bitumen-lined basket, or bucket and transferred it to the canal. This increased the irrigable distance further out along the Nile banks, increasing the amount of arable land and thus population that could be supported in an area and is still used in many parts of Egypt (Willcocks and Brown 1899; Dahab 1995). The *noria*, or simple waterwheel, was first used around 700 BC. It turned using the current, requiring no human interaction and freeing at least one labourer to complete other tasks. The later *saqia*, introduced in the Roman period possibly from Syria (Ménassa and Laferrière 1974), operated on the same principles but used pulleys controlled by oxen for power, effectively creating a well pump. This innovation required less human energy to achieve more irrigable area. Evidence of the *saqia* is associated with presence of *qadus* pots, which were extensively (but not exclusively) used with the *saqia* (Thomas 2008: 67). In areas that utilised these pumps, it can be suggested that skeletal robustness will decrease particularly in the lower limb. However, it is unknown whether these were adopted by any significant quantity of farmers along the Nile in Nubia, as they continued to use *shadufs* until at least 1995 in some places; Willcocks and Brown record 16000 *shadufs* in use in Nubia in winter 1899 (106).

It is not known which type of irrigation was used by the inhabitants of Gabati and Mis Island (cemetery 3-J-18). Although Gabati spans the time of the introduction of the *noria* and *saqia* into Nubia, there is no research on whether one of them would have been used by that group. The *saqia* was also a more complicated tool requiring the *qadus* pots and ropes and financial and technical investment (Willcocks and Brown 1899), which might not have been worthwhile to the Gabati individuals, whose grave goods do not identify them as high-status or rich. As the purpose of the *saqia* was to transport water further away from Nile, it is possible that Mis Island may have only required the *shaduf*; however, from the 4th century AD some *qadus* sherds were found at the nearby site of Umm Muri, indicating the presence of a *saqia* (Thomas 2008: 66). However, the pottery remains at Umm Muri were considerably more extensive than those at Mis Island, including more transport vessels. Remains of the *saqia* were not found at Mis until later in the Christian period (Welsby Sjostrom 2001). Other Nile islands present inconclusive evidence for adoption of the *saqia*. Büros Island in the Dongola Reach has two undated fired brick pillars at its upstream end that could have been part of a "peculiar type of saqia" (Zurawski 2002: 81). The post-Meroitic Saffi Island, also in the 4th Cataract, has very high banks that would have precluded both *shaduf* and *saqia* use, and excavators argue that drystone structures may have been used as dams in a wholly different method of irrigation (Zurawski 2005: 329); this is supported by an absence of *qadus* pots at Saffi. Due to the lack of specific evidence, it cannot be known whether advances in irrigation technology affected the groups under study, although this will be considered in the discussion.

6.3 Sites

This section discusses the background and archaeology of the three Sudanese sites, the outgroup English site, and the pilot study Egyptian site.

6.3.1 Jebel Moya

Jebel Moya is a cemetery site located in the Gezira Plain between the White and Blue Niles, about 250 km south of Khartoum. The original purpose of the excavation was philanthropic – as one of the first civilians to enter Sudan after Kitchener's occupation, Henry Wellcome (see Figure 6.3.1) decided to launch a massive excavation to provide employment to locals while furthering Sudanese academic studies of prehistory (Mukherjee *et al.* 1955).

Figure 6.3.1 Henry Wellcome overlooking the Jebel Moya site. Courtesy Wellcome Collection

The majority of the site was excavated by Addison between 1911 and 1914, revealing 3137 human skeletons in 2883 graves, although some graves contained only pottery and 25 were animal burials (Addison 1949; Mukherjee *et al.* 1955; Brass and Schwenniger 2013); see Figure 6.3.2. The site was found to cover 104,000 square meters, and was described by Addison as "one vast graveyard" (Mukherjee *et al.* 1955: 2). The collection, reduced to a few hundred skeletons due to poor transport and storage conditions, is now housed at Cambridge's Duckworth Laboratory. Of these, 2903 informational cards remain, 335 of which have all skeletal measurements, 1135 have some, and 1442 have none. By the time Mukherjee, Rao, and Addison examined the collection in the 1940s and 50s, it had been reduced to its current numbers (Mukherjee *et al.* 1955). Currently, 544 individuals are available for study, many of which are represented by only a few elements. Almost half of the graves did not contain grave goods, and the rest contained small groups of beads and some pottery; the rest of the finds were from extragrave stratigraphy, and divided into three main occupation levels entitled B, C, and D. Unfortunately for future researchers, close attention was not paid to stratigraphy for the first season of excavation, no sections were drawn, and the strata from which the graves were originally dug were not recorded until after 1912 (Addison 1949). Additionally, erosion and weathering were uneven across the site, causing variation in stratigraphic exposure.

EXCAVATION IN PROGRESS 1913–14

Figure 6.3.2 Jebel Moya excavation in progress. Courtesy Wellcome Collection

Addison and Kirwan began examining the pottery and other artefacts in 1937, concluding that strata A (topsoil) and B were deposited during the Napatan period, placing the site's abandonment before the start of the Meroitic period (Addison 1949: 253), a conclusion carried through to the 1990s by Gerharz (1994). However, new dating by Brass utilising optically stimulated luminescence in combination with stylistic variation of graves and artefacts has narrowed the time frame of the cemetery's deposition to a few hundred years, making analysis of skeletal material more promising. The new dates from Assemblage 3, which encompassed most of the burials, revealed them to be from the early, middle, and late post- Meroitic period (1st century BC-mid first millennium AD); however, the pottery assemblage at Jebel Moya lacks any Meroitic-type pottery, making it unique for this period. Jebel Moya ware has been found at nearby Abu Geili alongside Meroitic pottery, indicating some sort of trade network. In addition, no agricultural artefacts such as sickles have been found at Jebel Moya, lending credence to the hypothesis that those buried practiced a pastoral lifestyle, possibly focused on cattle herding. This argument is bolstered by the relatively late date of the burials compared to the pottery as well as the paucity of artifacts, argued by Bradley (1992) to be a marker of nomadism. Assemblages 1 and 2 dated to centuries prior with no associated burials; the individuals from these earlier stages may have been buried elsewhere, as is common in semi-sedentary or semi-nomadic groups (Brass and Schwenniger 2013; Bradley 1992). Arguably, individuals who died elsewhere could have been returned to the site at a later date, but the excavators did not note any evidence of dismemberment or binding of bodies. It is possible they were not looking for evidence of long-distance reburial, but their notes are sparse; the only site plan in existence is shown in Figure 6.3.3 and shows most of the skeletons to be in alignment and positioned either supine or semi-flexed on their sides. Although Addison noted possible evidence of habitation including burnt clay and calcium carbonate floor surfaces from Stratum C (1949: 97), his notes are not specific about where on the site the floors were found or with which period it might be associated (Brass 2015: 75). There were also hearths containing sherds, animal bones, and broken querns. Brass's argument that there was local habitation in the later period was based on these hearths, the local origin of the pottery temper, and the co-incidence of the majority of the burials with the Assemblage 3 pottery (2015: 78). The contemporaneous presence of the agro-pastoral sites of Abu Geili and Jebel Tomat in the Jebel Moya vicinity could indicate groups with distinct cultural identities based on modes of production who were interacting in the White Nile-Blue Nile region (2015: 155).

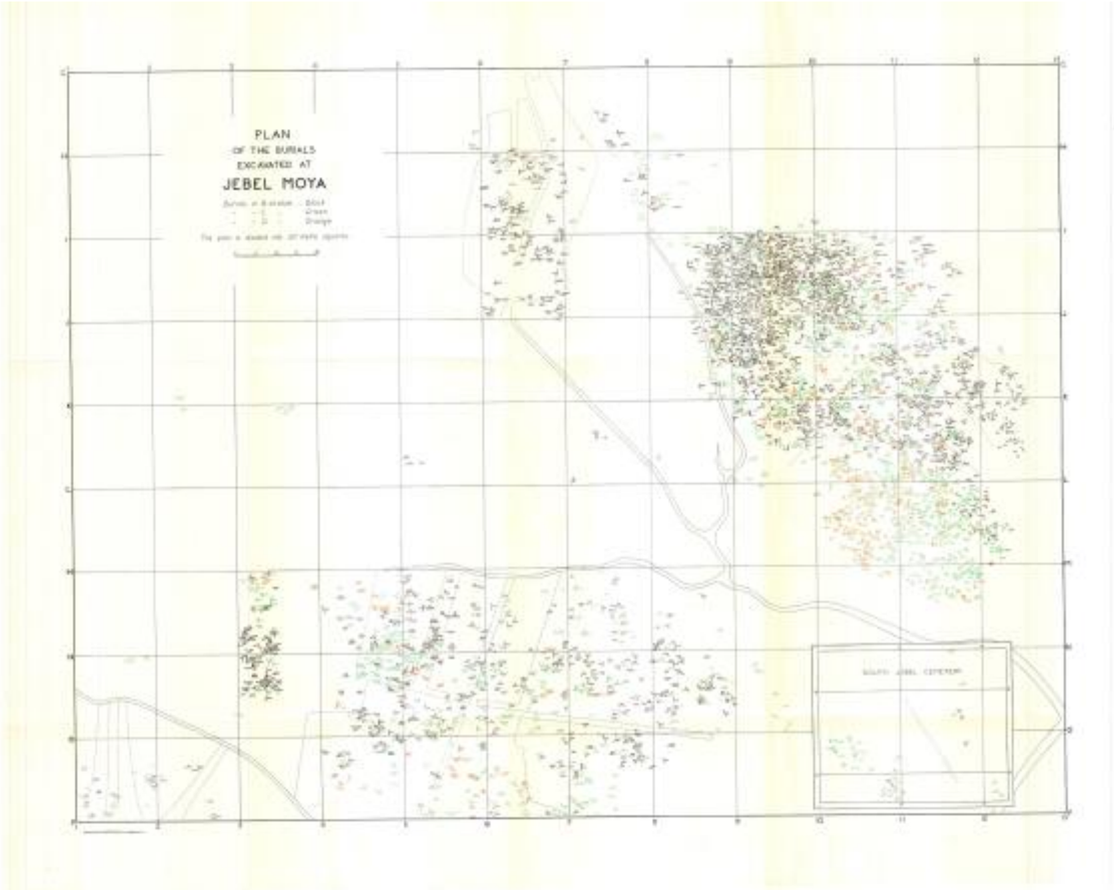


Figure 6.3.3 Site plan of burials at Jebel Moya. As taken from Addison (1949).

Pottery from the four strata determined by the Wellcome expedition at the beginning of the 20th century have been recently re-evaluated by Brass and Schwenniger (2013) and roughly corresponded to three time periods: the early fifth millennium BC and temporal equivalents to the late Kerma and Meroitic periods. The majority of the burials dated from the last time period, corresponding to pottery Assemblage 3, dated by optically stimulated luminescence to first century BC to the mid-first millennium AD. However, it should be noted that both pottery assemblages from the second and third periods were local traditions and not those of Kerma or Meroë. Despite this fact, links were visible via imports of prestige goods. Brass posited that during the Meroitic period, the individuals buried were mobile pastoralists and traders with a central burial ground along the route of their trade network (Michael Brass, *pers. comm.*).

The sex of the skeletons was initially assessed by the excavators in situ (Figure 6.3.4). While original field sex estimates found a considerably higher number of females, leading to the proposal of theories of wars resulting in males being buried away from home, and capturing or enslaving women from other groups, Addison's re-evaluation found 46% female and 54% male by combining the male and possible male categories and the female and possible female categories, which was accounted for by random fluctuation in society, bias in preservation as male long bones tend to be thicker and stronger, or differing evaluation methods practiced by the three different anthropologists hired each year of the excavation (Mukherjee *et al.* 1955: 10), a problem still evident in the field today. The three anthropologists present in the third and fourth seasons in 1913-14 – Hambly, Hussey, and Oldham – consistently disagreed and re-assessed each other's notecards, with much of the updated sex assessments focusing on younger individuals who may not have developed the musculoskeletal markers characteristic of adult males. Mukherjee called the second season's sex assessments by Derry the most accurate, although Derry was working alone and thus had no one to correct him. Similar disagreements were present for the long bone and cranial measurements. Addison's comments revealed that the number of labourers and the speed of excavation could be partly to blame, as local workers retrieved more skeletons than the anthropologists could reasonably process, leading to mistakes and arguments due to overwork (1949: 78).

Figure 6.3.4 Opened graves at Jebel Moya. Courtesy Wellcome Collection.

Original examinations attempted to find evidence of interbreeding between local and immigrant populations based on skull shape, but found that there was little to support this; the skulls were found to be internally homogeneous, euencephalic, mesoprosopic, and orthognathous (Mukherjee *et al.* 1955: 71). Mahalanobis D^2 distance based on skull measurements identifies the Ibo as the closest related group, followed by the Cameroons and Nubian C-Group, but maintains a considerable distance from any clusters of ethnic affinities. Statistical studies of measurements for the Jebel Moya skeletons, despite low sample size, revealed that they were quite tall compared to individuals from surrounding regions. The Jebel Moya males were found to be 175.6cm tall and the females 163.2 cm, using regression equations calculated for African Americans by Trotter and Gleser (1952). Thus when assigning racial groups, Mukherjee *et al.* (1955: 99) could not place the Jebel Moya inhabitants in any modern group with confidence as they were tall but long-headed. Mukherjee *et al.* (1955) also found that they were “not platymeric nor platycnemic” – in fact, they were eucnemic with a tibial index of 70.3 for males and 71.2 for females, pooling both sides. Irish and Konigsberg (2007) conducted a similar study to Mukherjee *et al.*’s, attempting use dental traits from similar geographic samples to reassess the Jebel Moya inhabitants’ ethnic affinities. Noted differences in dentition existed between sub-Saharan and North African groups, with the former being mass-additive (more features on the dentition) and the latter mass-reductive (fewer additional traits and an absence of the upper third molars). Irish and Konigsberg (2007:b151) found more cohesive grouping by geographic distance than Mukherjee *et al.*, but Jebel Moya was still an outlier; additionally, the dental traits were closest to North Africans while craniometrics placed them closer to sub-Saharans, possibly indicating population admixture (Figures 6.3.5 and 6.3.6, respectively).

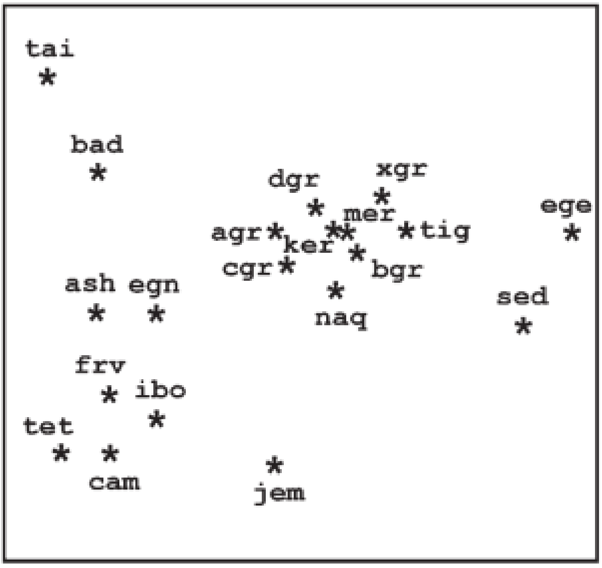


Figure 6.3.5 Mahalanobis groupings of North Africa from Mukherjee *et al.* (1955: 85), rotated 90° by Irish and Konigsberg (2007: 150), who noted the erroneous location of the Badari sample. The original graph did not include axes or scale.

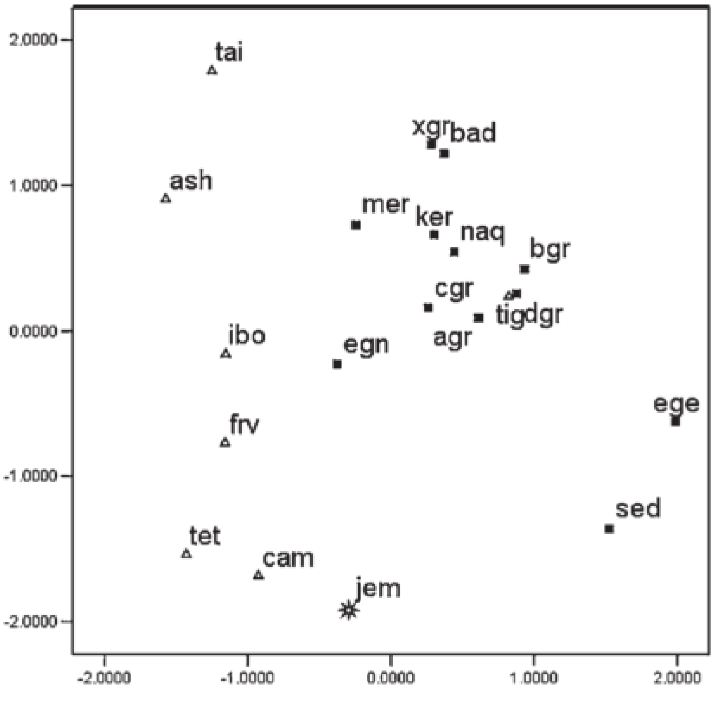


Figure 6.3.6. Two-dimensional MDS Mahalanobis D^2 of 19 dental traits. This chart is rotated 90° to the right from the previous; sub-Saharan groups are represented by triangles and North African groups by squares. As taken from Irish and Konigsberg (2007:149).

Following the earlier ideas of Addison (1949) and Gerharz (1994) and considering the internal heterogeneity of the pottery, the authors posited Jebel Moya as a "seasonal meeting place of widely distributed segmentary family units, the common identity of which was maintained by their periodical cohabitation there" (Gerharz 1994: 330).

6.3.2 Gabati

Gabati is a cemetery site on the east bank of the Nile, approximately 260 km north of Khartoum and 40 km north of the ancient city of Meroe, placing it in the heartland of the Meroitic empire (Edwards 1998). The graves and individuals therein can hypothetically be used to answer questions about the diversity of burial practice within the Meroitic and post-Meroitic context, and links can be drawn between centres of pottery and craft production during and after the empire period.

Originally identified in 1993 by the Sudan Archaeological Research Society (SARS) in surveys in advance of imminent road construction, Gabati was surveyed that year and a larger excavation was carried out the following year (Edwards 1998; Welsby *pers. comm.*). The cemetery lying under the proposed roadway was completely excavated, and a sample of graves from the larger area were excavated as well. Preference was given to Meroitic and post-Meroitic graves as the focus was the development of a cemetery chronology based on non-skeletal remains. The graves covered the Meroitic period from the 3rd-4th centuries BC to the early Christian and medieval periods, although evidence linking Christian-era graves to the Nubian Christian kingdoms was absent. Radiocarbon assays were carried out for a number of graves, although the later graves were over-represented in the assay as they had a higher number of dateable wooden artifacts (Edwards 1998).

The 63 Meroitic graves excavated were found to contain 124 burials (Edwards 1998: 196), shown in Figure 6.3.7. Four graves had mudbrick superstructures; the rest lacked superstructures but were possibly originally covered by a gravel mound, now eroded. Two types of substructure were present: the more common was an east-west shaft leading to a transverse oval chamber oriented north south, and the less common – represented by only three graves – was an east-west shaft leading to a rectangular axial chamber also oriented east-west. The burials, when found in situ rather than disturbed, were loosely or tightly flexed on a north-south axis. Of the 32 undisturbed enough to observe orientation, 86% had their heads to the south, 19 of whom were on their left side facing west (Edwards 1998: 194). Aberrant burials were of the "Egyptianised" style, dorsally extended on an east-west axis with heads to the west.

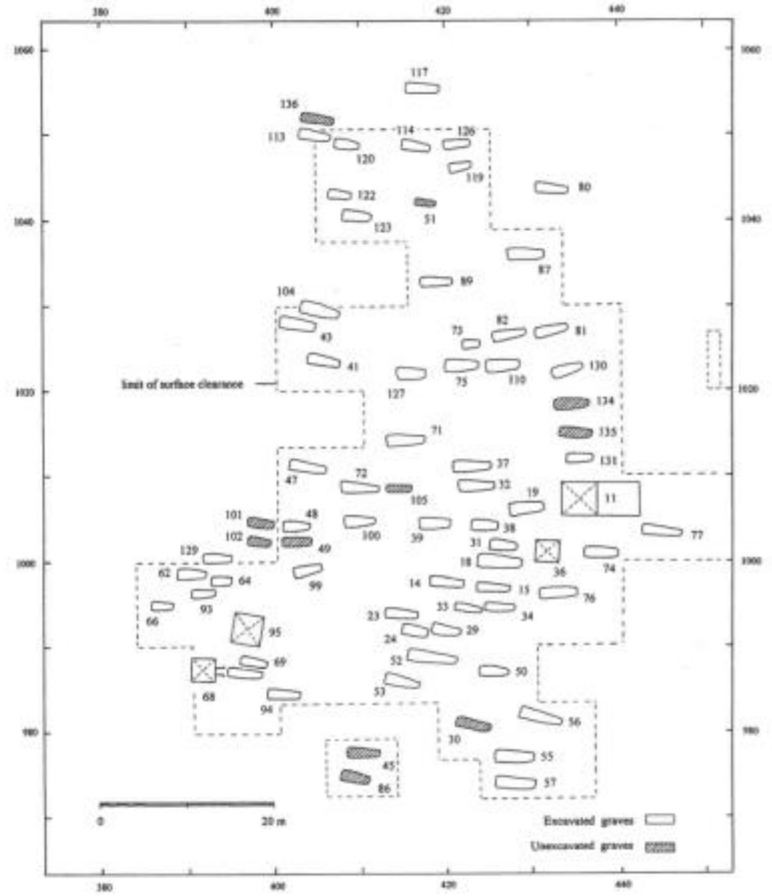


Figure 6.3.7. Plan of the Meroitic graves at Gabati. As taken from Edwards (1998: 12).

The most common artifacts in the Meroitic-era burials were wheel-made pots. Rose and Smith (1998) identified 13 wheel-made pottery forms and an additional 9 handmade forms. There were a number of changes in style over the Meroitic period, dividing the site into an early Meroitic period and a late Meroitic period. The early period, dated to the 2nd century BC to 1st century AD, was characterised by large jars and few open forms. Many of these large jars, some of which could hold almost 20L, saw extensive use before their final deposition (Rose and Smith 1998). The later group lacked dateable samples, but features more open forms and smaller jars concurrent with a decline in manufacturing technique and increased irregularity; parallels can be drawn with pottery from Kadada and Meroe (Edwards 1998). Other burial artifacts included beads made of faience, carnelian, quartz, black stone, and ostrich eggshell, many of which were found in positions indicating strung jewelry; ivory objects, possibly bowls or kohl pots; bronze rings; silver signet rings; ear and nose studs; wood fragments; and fragments of wool textile and leather.

The post-Meroitic graves comprised three different types of burials, shown in Figure 6.3.8. The earliest, dated to the 6th-7th centuries AD (and no earlier than the 5th century), are 38 stone-clad tumuli with some linear arrangement containing 32 individuals (Edwards 1998). The tumuli are constructed of gravel redeposited after the excavation of burial chambers and shafts similar to tombs in the Dongola Reach, with some ash and charcoal deposits indicating the use of small fires in funerary rites. The substructures featured a steeply sloping entrance shaft on an east-west axis terminating in an oval or semi-circular chamber with a sloping roof. Two aberrant shafts were on a north-south axis. The chambers were clearly constructed to hold contracted burials; the undisturbed bodies were mostly lying on their right sides, heads to south and facing east, which appeared to be the standard orientation for this time period, appearing at Bauda and Abri-Missiminia. Edwards pointed out that although the orientation was similar to that of the Meroitic period, the individuals were facing towards the entrance to the tombs rather than away from them (1998: 204). A significant difference was the appearance of wooden beds or biers in the tombs, similar to those at the cemetery at Meroe.

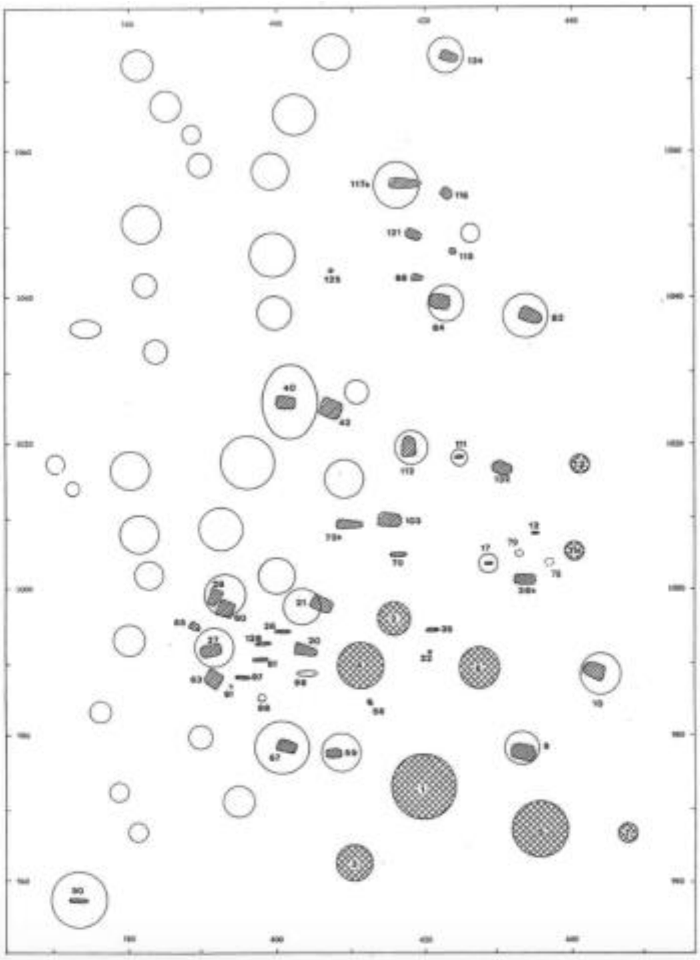


Figure 6.3.8. Plan of the post-Meroitic and Medieval graves at Gabati. As taken from Edwards (1998: 70).

The human remains were examined by Judd (2004; Judd 2012). She found a relatively equal distribution of males and females in both periods and a higher number of individuals dying before age 35 and most dead before age 50, which is attributed to either the small sample size or the era. A higher proportion of subadults died in the post-Meroitic period than the Medieval, which was the opposite of the situation at Kulubnarti and Soba East, but this was again attributed to sample size (Judd 2004). In the paleopathological analysis, Judd (2012) found a higher prevalence of cribra orbitalia[7] in Medieval adults than children, but it only occurred in children of the Post-Medieval period. Once again, the Medieval period

---

[7] Cribra orbitalia is a pitting within the eye orbits argued to be linked to iron-deficiency anemia (Waldron 2009).

only included 6 subadults so sample size may have affected significance. Additional pathology and trauma listed by Judd included clavicular and skull fractures, osteoarthritis, and intervertebral disc disease. 40% of females and the majority of males showed evidence of minor traumas (Judd 2004). Ongoing British Museum research is investigating pathological spinal conditions possibly associated with agriculture.

6.3.3 3-J-18

3-J-18 was a cemetery and church site on Mis Island excavated as part of the Merowe Dam Salvage Project. The 3-J-18 area was 68m in length and 27m in width and contained a mud brick and mastaba church and a cemetery (Welsby 2003), although four burials appeared to predate the church's construction (Ginns 2010b).

Although originally called for in 1993 due to the imminent construction of the Merowe Dam, the Sudan Archaeological Research Survey was only able to begin excavation in 1999. Their concession for this project was between Amri and Kirbekan, a section 40 km in length upstream of the 4th Cataract and contained sites from a number of periods from Neolithic to Medieval. The area included a number of islands, all of which were surveyed, the major monuments recorded, and as many sites as possible located; the same was done for any sites from irrigation areas on the riverbank to the first ridge and sites in wadis and paleochannels as these were all in imminent danger of flooding. 39 sites were surveyed and recorded if not fully excavated (Welsby 2003).

Complete excavation of the cemetery was undertaken in the second season in 2005-6. The cemetery shows three phases: Phase I, containing four burials, predated the church. These graves, unlike those of the later phases, were aligned north-west to south-east. Two were covered with stone slabs, and one contained a large vessel. The excavators tentatively suggested a date of post-Meroitic or early Christian (Ginns 2010a). Phase II contained 173 burials with a variety of monument types (fired brick, mud brick, mastaba, mixed, and unidentifiable). These burials were oriented east-west with most heads at the west end, and the individuals were positioned supine or on their left or right sides (62, 54, and 43 individuals, respectively). Most grave cuts had no internal structural adornments, with only a few graves containing three stones over the individual's head (Ginns 2006). Phase III contained 42 burials: 19 supine, 12 on the right side, 9 on the left, and 2 prone. All of the Phase III burials had stone monuments, some of which contained upright stones, a typical feature of Islamic-period burials. This phase may also postdate demolition of the church. No additional grave goods were present besides 3 ceramic vessels, although many textile fragments were preserved, indicating that the deceased were wrapped in woven shrouds and bound with string; some were wearing beaded jewelry, rings, and earrings. Two individuals had jewelry with metal cross pendants. Three pits of unidentified purpose also located within the cemetery contained ceramic vessels, and one grave contained an animal spine (Ginns 2010a).

Preliminary age and sex estimation of the human remains was conducted in the field by Ginns (2006). 3-J-18 had a lower percentage of infant and child burials compared to the other Mis Island cemeteries of 3-J-10 and 3-J-11, indicating contemporaneous use of all three and a preference for burying adults near to the church, reinforced by the different monument types found at 3-J-18 (Ginns 2006). Preservation at 3-J-18 was much better than at the other two cemeteries, with the aforementioned preserved textiles and considerable amounts of soft tissue present (hair, skin, nails, and brain matter), with some individuals almost wholly naturally mummified.

As of 2016, no in-depth analysis has been published of the 3-J-18 skeletal material. Many individuals are still awaiting analysis by Institute of Bioarchaeology volunteers, the author included. Currently, individuals have been found that present evidence of tuberculosis, leprosy, brucellosis, and minor fractures (Daniel Antoine, *pers comm*).

6.3.4 Chichester

Chichester is a cathedral town on the English south coast in West Sussex, 87 km from London, with continuous occupation since the 1st century AD, when a Roman city was established; the town was re-planned and refortified in the 9th century (Hart *et al.* 2012: 4). The excavation, conducted by Archaeology South-East in 2011-2012 following three prior planning excavations in 2005-2008, investigated the burials underneath Eastwall Car Park

(Rando 2016). The season focused on uncovering the burials dating from the 10th-19th century for bioarchaeological and funerary archaeological analyses. Key questions centered on comparing diet, disease, dental pathology, and social status through time, and comparing the post-Medieval skeletons to their contemporaries in larger English cities. This site was chosen as an outgroup to rule out possible genetic similarities influencing tibial diaphyseal shape between the Sudanese groups.

The excavation uncovered a single Roman burial with coffin nails, evidence for burial from that period slightly west of the Roman cremation cemetery nearby. This grave was in an area used as a quarry and later refuse dump (Hart *et al.* 2012: 12); many pits were found to contain animal bones, coarse pottery, iron, charcoal, and other household and industrial waste. Intermixing of 12th-13th century material indicates this pit was left at least partially open for centuries (Hart *et al.* 2012: 13). In the Medieval period, the area became a cemetery.

In total, 1730 skeletons from 1727 graves were excavated and seven burial types identified. The most common were basic single inhumation shroud burials (1365), followed by basic single coffin burials (288). 55 individuals were buried in coffins inside brick tombs, 13 had pillow burials with greenstones arranged around the head, and the rest were variations on these types. The shroud burials were all arranged ENE-WSW or NE-SW, and all but two with the head towards the west. Although all individuals were supine, arm position varied: arms over the abdomen, hands crossed over the pelvis, or arms at the sides (Hart *et al* 2012: 15). Two graves contained multiple inhumations – one contained two adults side by side and the other an adult and fetus. All coffined burials were single interments, although two were stacked, possibly non-concurrent interments in a family plot (Hart *et al.* 2012:18). Most burials date from 1550-1950 (Rando 2016).

The skeletal analysis was performed on-site. The site osteologists divided the skeletons into three categories based on preservation; only the 430 in a state of good preservation including retention of age and sex characteristics were retained for further study, while the rest were reburied (Hart *et al.* 2012: 20). Various pathological changes were found, including leprosy, DISH (see Chapter 3.4), calcified cysts, and rickets; a study of osteoarthritis and social class found lower rates of major joint osteoarthritis in upper-class females than lower-class females, but no difference in males, indicating differential labour patterns for females but not males (Rando 2016). A map of Chichester is shown in Figure 6.3.9.

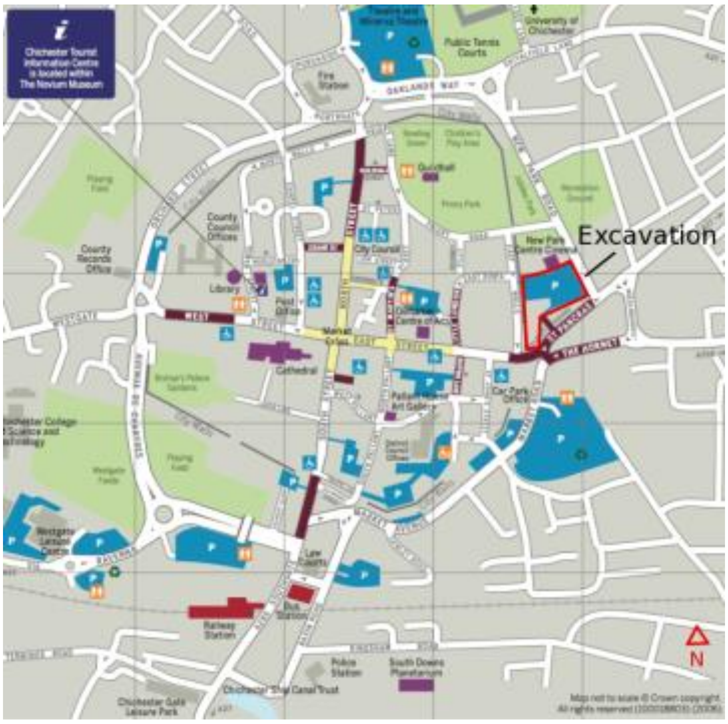


Figure 6.3.9 Map of Chichester, UK, with the cemetery site highlighted. As taken from Chichester City Center Partnership.

6.3.5 Naqada

The pilot study uses a sample of individuals from Naqada. As the decision was made not to include Naqada in the final analysis, it will only be discussed briefly here. Naqada is a predynastic Egyptian site located in Upper Egypt around 240 km north of Aswan. The excavation of Naqada took place between 1894-95 and was supervised by Flinders Petrie (Petrie 1896). He identified three cemeteries and a settlement, and the pottery from 900 graves was instrumental to Petrie's seriation and typology of the predynastic period. The cemeteries date from three cultural periods, Naqada I or Amratian (4000-3500 BC), Naqada II or Gerzean (3500-3200 BC), and Naqada III or Dynasty 0 (3200-3150 BC). These phases see Naqada becoming integrated into an identifiably Egyptian culture and incorporate more elaborate grave goods and inscriptions of kings' names. Evidence of trade with Nubia, the western desert, and even the eastern Mediterranean is seen as early as the Naqada I period, indicating that despite the lack of a unifying state, extensive trade networks were still in place (Shaw 2000). A map of Egyptian sites including Naqada is shown in Figure 6.3.10.

Figure 6.3.10. Map of Egypt. Naqada is west of the Nile. Courtesy Claire Thorne.

Petrie originally assigned the human remains at Naqada and its sister site Ballas to the "New Race", which he assumed were the remains of foreigners who invaded Upper Egypt sometime after the Old Kingdom, rather than the indigenous Egyptian groups who constitute those buried in the predynastic period. They were distinguished in burial position with their heads to the south, lying on the left side in a flexed position (Petrie 1896: 8). When the site of Naqada was found to be predynastic, this assignation was discounted but Petrie's Dynastic Race theory persisted (Lovell 1994). The Naqada remains were first examined by Pearson and used as part of a cranial racial classification system. More recently, the dental morphology has continued to be studied by Lovell (1994), Lahr (1996), Brace *et al.* (2006), Irish (2006) and others to examine relatedness. The human remains from Naqada are stored at the Duckworth Collection in Cambridge.

6.4 Specimen selection criteria

This study examined over 250 individuals overall and at least 40 from each assemblage. Thus only collections containing assemblages where n>40 were used. The standards for inclusion of any particular skeleton are as follows:

1. Adult: for present purposes, this is defined as the proximal and distal epiphyses and the tibial tuberosity fused to the tibial diaphysis, indicating that the individual is over 18 years (Bass 2004).
2. At least one tibia is complete (that is, both proximal and distal ends and shaft are in stable condition and, if broken, can be successfully aligned using conservation-approved reversible methods) and not pathological
3. The midshaft of the tibia is free from mummified tissue or residue blocking measurement or scanning

The study attempts to include an even sample of males and females (as previously assessed) and adults of different age stages.

For the most part, pathological changes to bone do not affect this study. Any tibiae with pathological or traumatic deformations were excluded. Some of the medieval assemblages feature a diverse array of pathological conditions, including tuberculosis and leprosy, but if these diseases were acquired after adolescence - which is the case in most skeletons examined - they would not affect external tibial shape. Diseases such as rickets that affect the tibia result in the exclusion of those skeletons from the study, as they would affect the movement of the individual in a biomechanically different way than undiseased tibiae. Individuals with periosteal reactions were excluded as that can also affect the external shaft shape and could indicate a painful condition in the leg, also affecting gait biomechanics.

6.5 Frequencies of individuals

This section presents the frequencies of individuals from each site. Table 6.5.1 displays the distribution of individuals from the four sites used in this study. The highest proportion of individuals are from 3-J-18 (n=87, 34.3%), the Mis Island site, and the least from Chichester, the control site (n=42, 16.5%). Preservation was better at Jebel Moya and 3-J-18 than at Gabati, explaining the small size of the assemblage. As discussed in Chapter 8, only adult skeletons were used in this study, so the assemblages are actually larger than the numbers given here. Jebel Moya comprises 544 individual adults, although most of those are fragmentary (Okumara n.d.). Gabati includes 124 burials, 106 of which are sexed adults (Judd 2012). 3-J-18 includes 217 individuals, 144 of which are adults (Ginns 2010). While the skeleton counts for Chichester differ from the total excavated, there appear to be around 330 adult individuals currently under study (Carolyn Rando, *pers. comm.*). Note that while Jebel Moya, Gabati, and Chichester individuals were excluded due to poor preservation, many individuals from 3-J-18 were excluded due to good preservation: partial natural mummification obscured part of the legs, sometimes still connecting the tibiofibular complex or ankle joint and thus making either total length inaccurate or one side of the tibia obscure to scanning.

Site	Frequency	% of Total Assemblage	% of Sample
Jebel Moya	70	12.80%	27.60%
Gabati	55	51.88%	21.70%
3-J-18	87	60.40%	34.30%
Chichester	42	12.70%	16.50%
Total	254	NA	100%

Table 6.5.1 Frequencies of individuals at each site. % of total assemblage indicates the percent of individuals with at least one complete tibia from the total at that site; % of sample indicates the proportion it comprises in this study.

Table 6.5.2 displays the distribution of individuals of each sex by site, showing roughly even numbers of males and females (and a small number of ambiguous/unassigned) at Gabati, 3-J-18, and Chichester, but a considerably smaller proportion of females at Jebel

Moya. Males (n=132, 52%) outnumber females (n=97, 38.2%). The ambiguous/unassigned category (n=25, 9.8%) are mostly those individuals whose pelves are in too poor a state of preservation to determine sex rather than individuals whose pelvic features led to an intermediate score of "3" according the Buikstra and Ubelaker guidelines (1994), discussed in Chapter 7.

	Jebel Moya	Gabati	3-J-18	Chichester	Total
Female	20	24	38	15	97
Ambiguous/unassigned	2	5	9	9	25
Male	48	26	40	18	132
Total	70	55	87	42	254

Table 6.5.2 Frequencies of each sex (female, ambiguous/unassigned, male) by site (Jebel Moya, Gabati, 3-J-18, Chichester), showing a fairly even distribution of sexes at all sites except Jebel Moya.

Table 6.5.3 displays the breakdown of age in the sample. Only 8 individuals (3.1%) are assigned to the older adult category: 5 from 3-J-18, 2 from Chichester, and 1 from Gabati; 6 are female and 2 male. The majority of individuals could only be assessed as "adults", masking any distinctions that could be found to be significant. This is most likely due to poor preservation of the pelves, particularly among the Jebel Moya individuals. Age is not normally distributed and is not expected to be as it is a death assemblage; when the adult category is removed, there is a steep slope as 94.9% of aged individuals fall into only two categories. Whether this category conflation affects CSG properties or GMM will be discussed in Chapter 9, though it should be noted that the lack of information about the medullary cavity and the lack of information about age are well-matched (Nikita *et al.* 2011: 427): the medullary cavity is affected by age-related bone loss, but it is unable to be examined using 3D scanning methods. Even if it were visible (utilising alternative technology such as CT scanning), the lack of age assignments for many of the individuals reduces the viability of the data, as such a high proportion can only be assigned "adult".

	Jebel Moya	Gabati	3-J-18	Chichester	Total
Adult	70	9	5	12	96
20-35	0	29	42	11	82
35-50	0	16	35	17	68
50+	0	1	5	2	8

Total	70	55	86	42	254

Table 6.5.3 Frequencies of individuals by age category (adult, 20-35, 35-50, 50+).

Table 6.5.4 displays the frequency of side used. The left side was preferred in this study (n=182, 71.7%), but in some cases the antimere was used due to damage or, in the case of many individuals in 3-J-18, partial natural mummification obscuring the bone surface and/or the proximal and distal ends; in a few instances, the entire lower left leg was preserved. In these cases, it was necessary to use the right side. However, the bilateral asymmetry test performed in the pilot study (see Chapter 7.8) showed that differences between antimeres was not statistically significant, and ImageJ enabled the cross-sectional images to be digitally flipped and appear as lefts.

	N	% of Sample
Left	182	71.70%
Right	72	28.30%
Total	254	100%

Table 6.5.4 Frequencies of individuals by side (left vs right).

Table 6.5.5 displays the proportion of the sample in each shape category. These shapes will be defined in Chapter 7.7 Most fell into the triangular category (n=71, 28%), followed by flat side (n=65, 25.6%). These will be discussed and further broken down by sex, age, and site in section 8.2. Shape is a categorical variable and is not evenly distributed: as shown below, 28% of individuals observed are in the triangular category and only 7.2% in ovoid. Shape distribution by site is discussed in each subsection below.

Shape	N	% of Sample
triangular	71	28.40%
droplet	41	16.40%
flat side	65	26.00%
half-moon	27	10.80%

diamond	28	11.20%
ovoid	18	7.20%
Total	250	100%

Table 6.5.5 Frequencies of individuals by shape category (triangular, droplet, flat side, half-moon, diamond, ovoid). 4 individuals are missing shape categories due to data glitches and are excluded from further shape analyses.

7 Methods

This chapter will cover the methods used in the study, including comparisons with other methods and reasons for selection. It reviews the criteria for selection of individuals from these sites based on age, preservation, and lack of pathological features. The second part reports the methods used for examination of midshaft tibial diaphyseal shape, including reasons for using these methods and not others used in the past, as well as the types of statistical analysis that will be conducted on the data gathered from the material. The third part presents the results of a pilot study performed on a subsample of the data set; it is a preliminary test of most of the methods presented and was used to improve and refine the methods.

7.1 Assessment of age and sex

It is valuable to assess age and sex of each member of a skeletal assemblage not only for demographic purposes (identifying whether the burial assemblage is representative of a living population), but also to examine subgroups within the assemblages. This is necessary to address the questions about the distribution of activities or behaviours between sex or age groups, as discussed in Chapter 2.6 (Hawkey and Merbs 1995; Robb 1998). The sex and age assessment techniques utilised here are common to all bioarchaeological investigations and rely on guidelines suggested by Buikstra and Ubelaker (1994), Brickley and McKinley (2004), and Bass (2004).

Age and sex for each individual was determined using methods developed by Phenice (1969), Todd (1923), Lovejoy *et al.* (1985), Brooks and Suchey (1990), and Acsadi and Nemeskeri (1970). Sex was determined using the following traits:

1. Pelvic traits: breadth and depth of the greater sciatic notch; overall shape of the pubis body; presence of the ventral arc; presence of the inferior ramus ridge; and presence of the subpubic concavity. These are shown in Figure 7.1.1.

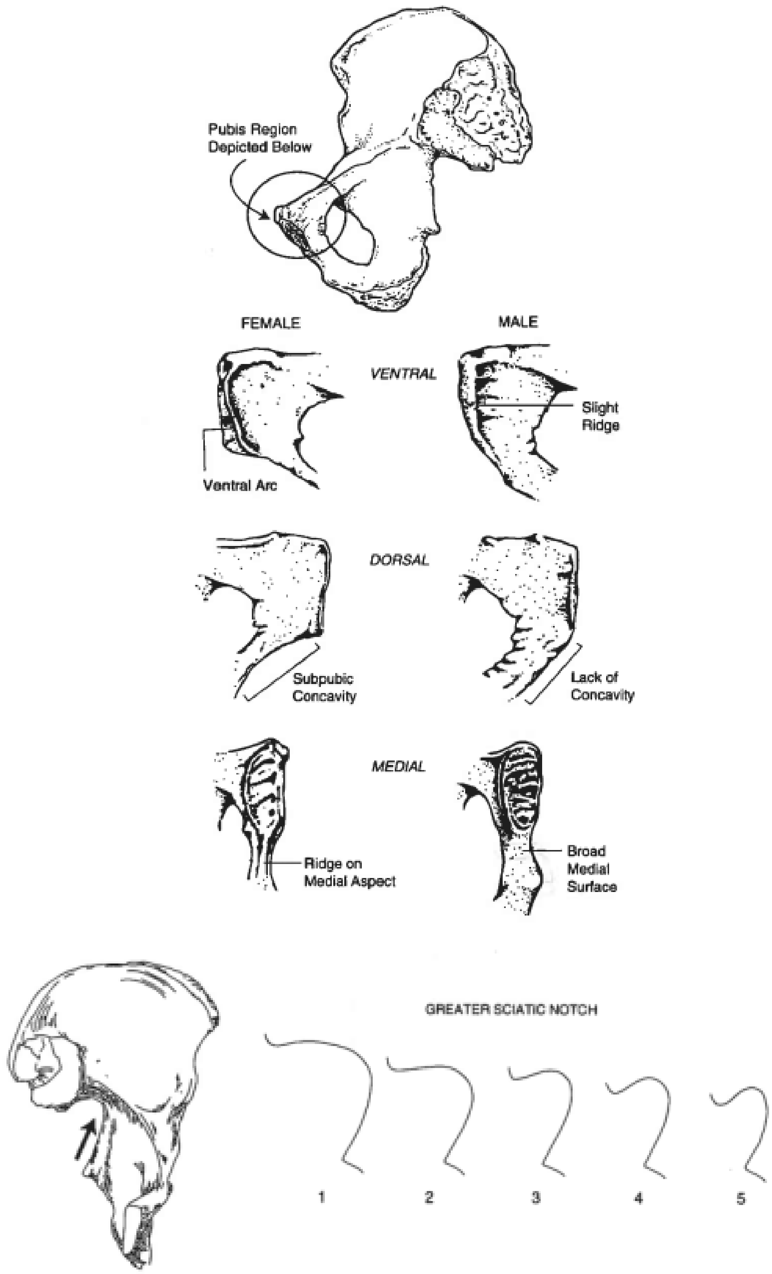


Figure 7.1.1. Sex assessment criteria using the pubis (top) and greater sciatic notch (bottom), with female traits on the left (1) and male traits on the right (5), as taken from Buikstra and Ubelaker (1994: 17-18) after Phenice (1969).

2. Skull traits: size of the occipital protuberance; rugosity of nuchal lines; prominence and breadth of the mastoid process; rugosity of the supramastoid crest and temporal line; prominence of the glabella; and width of the orbital

margin. It has been noted that males from this region tend to have more gracile skulls than the males of European ancestry on whom the standards were based (Lahr 1996), so the pelvis always takes precedence in assigning sex. This is shown in Figure 7.1.2.

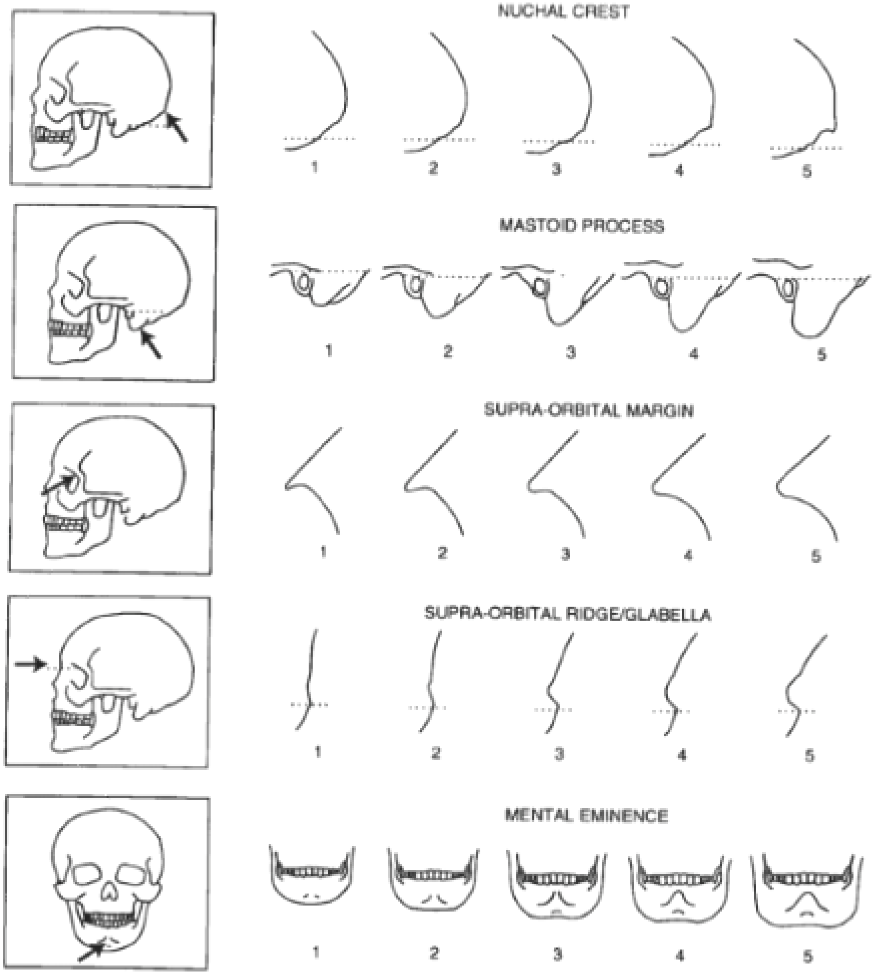


Figure 7.1.2. Sex assessment criteria using the skull, with female towards the left (1) and male towards the right (5), as taken from Buikstra and Ubelaker (1994: 20) after Acsadi and Nemeskeri (1970).

Categories for sex after are "female", "probable female", "unassigned/ambiguous/unknown", "probable male", and "male". For purposes of data analysis, these have been compressed to three categories, combining "probable female" with "female" and "probable male" with "male". For this project it was necessary to make a clear distinction between males and female, so “unassigned” individuals were rejected and the two “probable” categories were integrated into the respective male and female categories.

Sex and age assessments for 3-J-18, Gabati, Chichester, and most of Jebel Moya were performed by the researcher (SH). It should be noted that many skeletons, especially from Jebel Moya, were not associated with a pelvis or skull due to poor preservation. The tibiae from Naqada used in the pilot study were in a box with no additional context. In both of these cases, the sex was marked “unassigned/ambiguous”.

This study only examined adult individuals to eliminate growth-related morphological change. Adulthood was determined by complete fusion of both tibial epiphyses and the tibial tuberosity, indicating cessation of growth. Additionally, age stage was estimated in order to determine whether older individuals had undergone morphological change in adulthood. Age was estimated using the following two methods:

1. Morphology of the pubic symphysis using the Suchey-Brooks method (Brooks and Suchey 1990): depth of ridges and furrows; degree of delineation of dorsal margin, dorsal platform, ventral rampart, and extremities; and presence of ossific nodules. This is shown in Figure 7.1.3.

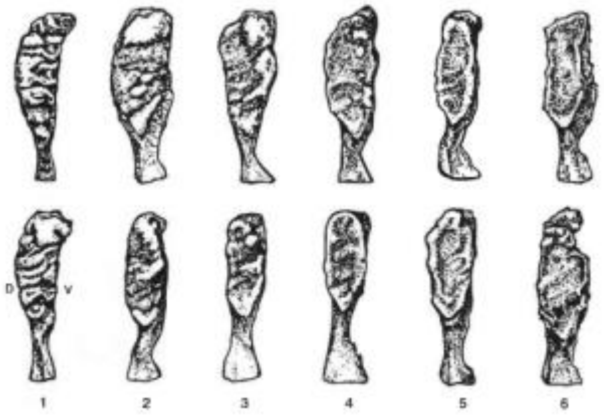


Figure 7.1.3. Illustrations of the Suchey-Brooks pubic symphysis scoring system for females, with younger individuals towards the left and older individuals towards the right, as taken from Brooks and Suchey (1990). Males follow a similar pattern, not shown here.

2. Morphology of the auricular surface using Lovejoy's method (Lovejoy *et al.* 1985).

These methods allow researchers to assign skeletons to broad age categories which will later be used to compare differences in shape between groups. Categories for age stage are 20-35 years ("young adult"), 35-50 years ("middle adult"), 50+ years ("older adult"), and unknown ("adult"). As it is almost impossible to assess age to an exact number of years, there may be overlap in the categories; it has been shown that many researchers overestimate the age of young adults and underestimate the age of older adults (Bocquet-Appel and Masset 1982). As age-related changes in long bones are more likely to occur in the medullary cavity rather than on the external surface of the bone (Kiebzak 1991; Beck *et al.* 1992), exact age in years – which is nearly impossible to determine in skeletons of this antiquity – was not relevant. As with sex, skeletons unassociated with a pelvis were marked "adult" as age stage cannot be determined with confidence.

7.2 Macroscopic and Metric Analysis

After assessing age and sex, the tibiae were examined for any evidence of pathological developments (for instance, periosteal ossific reactions, healed fractures, sabre shins); as discussed in Chapter 6.3.3, if any pathology of the tibia was present, that individual was excluded from the analysis.

Musculoskeletal stress markers were also examined for the purpose of comparing morphometric shape to habitual activity-induced musculoskeletal robusticity. As discussed in Chapter 3.3, increased activity theoretically results in more robust musculoskeletal markers at the point of attachment between the muscle and bone. A more robust attachment indicates a higher level of habitual activity. For this study, the robusticity of the soleal line was assessed using the scale established by Hawkey and Merbs (1995) in order to test a correlation between tibial diaphyseal shape and MSM robusticity. For a muscle insertion site, the categories are as follows: 0=absent; 1=faint (a slightly rounded cortex), 2=moderate (uneven cortical surface without distinct crests or ridges), 3=strong (distinct, sharp crests and ridges), and 4=stress lesion, which the authors presented as the next stage in a continuum of robusticity (Hawkey and Merbs 1995: 329).

Next, measurements of tibial intercondylar length, anteroposterior and mediolateral midshaft tibial diameters, and femoral head diameter were taken by the researcher. The purpose of measuring was threefold: first, to ensure accuracy of scale on the 3D models and subsequent 2D sections. Second, measurements were taken to measure directional asymmetry and sexual dimorphism. Third, measurements of the femoral head (when possible) enabled standardising for body size (Auerbach and Ruff 2004; Nikita *et al.* 2011).

The tibiae were measured by hand with an osteometric board and Mitutoyo digital plastic calipers. First, the tibia was placed longitudinally on an osteometric board with the proximal epiphysis at the static end and the distal epiphysis at the sliding upright board and the anterior surface pointing up, with the medial and lateral condyles against the static board and the intercondylar eminences through the hole, shown in Figure 7.2.1. This measurement, *tibial intercondylar length*, is a basic measurement for the tibia. In this study, it was used to test normal variation of individuals and then, in combination with femoral head diameter, to standardise size. Tibial intercondylar length will be referred to throughout this document as “length”.

Figure 7.2.1. Photograph of a sample tibia on an osteometric board, demonstrating the correct technique for measuring tibial intercondylar length. The intercondylar eminences are inserted through the hole at the static end and the sliding end touches the medial malleolus. S. Hackner 2016.

The midshaft was chosen for a number of reasons. First, it is easy to identify and measure by hand to ensure correct alignment and sizing between the actual bone and the digital version and is easily replicable. Second, as discussed in Chapter 2, the midshaft of the lower limb long bones experiences the most stress, and is tested in all biomechanical studies in the literature. In beam theory the midshaft experiences the most biomechanical stress and is correlated with terrestrial mobility (Stock 2006; Shaw and Stock 2011; Macintosh *et al.* 2014). Studies by Ruff and Hayes (1983b) and Minns *et al.* (1975) have shown that stress along the tibial shaft is variable (see Chapter 4.2), but that sexual dimorphism was highest at midshaft (Ruff and Hayes 1983). Third, the midshaft has been shown to have a high correlation between strictly periosteal and both periosteal-endosteal metrics (Macintosh *et al.* 2013), although the lowest rate of error was found to be slightly distal, between 29-35%. However, as the current study is comparing whole-bone sections, the error range at midshaft is minimal. Finally, the midshaft appears to be disconnected from body size, thus removing the effect of genetically- or environmentally-determined body size as a factor in tibial CSG values. Davies and Stock (2014) found significant negative correlations between body width and CSG values at midshaft, indicating that transformations at this location are linked to behaviour rather than body size, and that this negative correlation continues distally as the tibia tapers, concluding that the midshaft tibia region may be the best location within the lower limb at which to identify behavioral signatures from periosteal geometry" (Davies and Stock 2014: 834). More distal points on the shaft could have been tested, but the decision was made to use one that has been extensively researched in both sports science and anthropology, discussed in Chapter 4.

The *midpoint* (MP) was mathematically calculated as half the total length and measured using calipers with the tibia on the osteometric board to ensure accuracy. The *anteroposterior diameter* (AP) at midshaft is the maximum distance between the anterior crest and the posterior edge. The *mediolateral diameter* (ML) at midshaft is the maximum distance between the interosseous crest and the medial side, at 90° rotation from the anteroposterior diameter, shown in Figure 7.2.2. Measurements were taken three times and the average recorded. These midpoint measurements were used to calibrate the 3D scans.

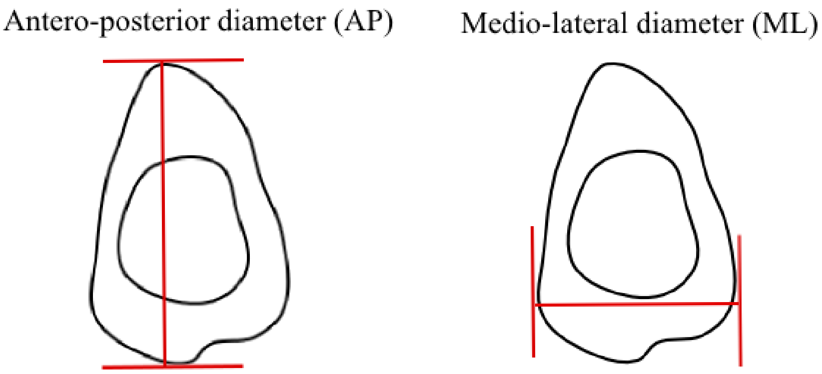


Figure 7.2.2. Diagram of measurements of the tibial midpoint's anteroposterior and mediolateral diameters, shown in cross-section. S. Hackner 2016.

Due to the variation in location along the shaft of the nutrient foramen, diameters at the foramen were not recorded for this study.

Femoral head diameter (FHD) is used to calculate body mass, which in combination with tibial length was used here to standardise size, discussed further in section 7.2.3. This measurement is taken in whichever direction the maximum diameter occurs. An example is shown in Figure 7.2.3.

Figure 7.2.3. Photograph of a sample femoral head showing measurement for maximum femoral head diameter in the superior-inferior direction using calipers. S. Hackner 2016.

7.2.1 Directional asymmetry

Directional asymmetry is infrequently observed in the lower limbs of humans, but has been observed in some studies of pastoral groups with no clear biomechanical or activity-based explanation. Given low rates of asymmetry, it was in the interest of time to scan only one tibia rather than both. In order to determine whether it was necessary to scan both tibiae of an individual, preservation allowing, tests of asymmetry were performed. As will be discussed in Section 7.9, there were not enough individuals from Jebel Moya with both tibiae preserved to allow for true comparison (n=9), so all lefts and all rights were compared by examining mean values. In the main study, tests of directional asymmetry were conducted using Gabati (n=35). Directional asymmetry (%DA), the measure of right or left preference, was tested for length and total area (see section 7.5.1) using the equation:

%DA = (right-left) / (average of left and right) * 100

as per Auerbach and Ruff (2006). However, %DA combines the relative frequency of right and left dominance with the absolute values of asymmetry within right and left dominant groups, so percent absolute asymmetry (%AA), which describes the amount of random asymmetry between sides, was also calculated using the equation:

%AA= (maximum-minimum) / (average of maximum and minimum) * 100

7.2.2 Sexual dimorphism

Sexual dimorphism is the difference in size between males and females in a group or population. As has been demonstrated by previous researchers, human males tend to have larger bones than females. Some populations may have higher rates of dimorphism than others, and some bones might be more dimorphic. Calculating the amount of dimorphism in each measurement of the tibia can indicate differences in the groups under investigation – for instance, greater dimorphism in tibial length may indicate preferential feeding for one sex or the introduction of one sex from an additional population (Agarwal and Glencross 20011; Larsen 2015), whereas dimorphism in midshaft diameter but not length may indicate differences in activity levels: Ruff (1987) tracked a decline in tibial anteroposterior bending strength from hunter-gatherer to agricultural to industrial populations. Sexual dimorphism is calculated as follows after Borgognini Tarli and Repetto (1986) and Wells (2012):

%SD = (male value-female value)/female value *100

This equation shows the numerical difference between males and females. Note that it slightly differs from the equations for asymmetry, as those are intended to produce the difference from a mean. Dimorphism was calculated for each measurement (tibial intercondylar length, both midshaft diameters, and femoral head diameter).

7.2.3 Standardising for body size

Femoral head diameter (FHD), the measurement of which is illustrated above, is used here to estimate body mass. Body mass is used instead of stature because mass can have a mechanical effect on bone building. As a primary weight-bearing element, the femoral head and body mass are functionally associated (Auerbach and Ruff 2004): an individual with higher body mass must place more weight on the lower limbs, contributing to higher loads. Estimating body mass using FHD is known as a “mechanical” method of assessing body mass, as opposed to the “morphometric” methods of measuring stature and maximum pelvic breadth (Ruff 2000), which could not be performed for this study due to the fragmentary nature of many of the pelves. While these methods can produce results slightly higher or lower depending on the assemblage, they are argued to be comparable; this is advantageous for assemblages where the pelvis is too poorly preserved to measure pelvic breadth but does have preserved femoral heads. Body mass estimation is important in many studies exploring the variation in size and shape of ancient human groups, particularly with regard to thermoregulatory adaptation (Ruff 2000: 269). As the diaphyseal measurements and cross-sectional properties of load-bearing skeletal elements (in this case, tibiae) are responsive to mechanical loads, it is necessary to quantify those loads: otherwise the conclusion of most studies would be that larger individuals (in humans, males) have higher cross-sectional geometric values than smaller individuals (females). However, this conflates size with strength and rigidity, which are not necessarily linked; it is misleading to use “unadjusted bone length alone” when comparing cross-sectional geometry and measurements (Ruff 2000: 282). It is possible that greater strength is masked by smaller overall stature, demonstrated by chimpanzees’ higher strength relative to size than modern humans (Ruff 2000: 288).

FHD was measured as described above and shown in Figure 7.2.3 in order to estimate body mass and standardise measurements, as robusticity and body mass are correlated (Pearson 2000). Normalising for body size utilised the following equations, after Auerbach and Ruff (2004):

$$\mathbf{BM_{female} = (2.426 * FHD - 35.1) * 0.9}$$

$$\mathbf{BM_{male} = (2.741 * FHD - 54.9) * 0.9}$$

$$\mathbf{BM_{combined} = (2.160 * FHD - 24.8) * 0.9}$$

The “combined sex” equation was used for individuals of ambiguous/unassigned sex.

The next step after physical examination was 3D scanning, described below.

7.3 3D Laser Scanning

This section covers the background of laser scanning and other techniques, explaining why the former is the most appropriate method for this study. Next, the specific methods used are covered, followed by the digital processing necessary to interpret 3D scan data.

Bone shape can be compared using a set of cross-sectional biomechanical properties that describe the strength of the bone in torsion and bending (Lieberman *et al.* 2004; Davies *et al.* 2012; Macintosh *et al.* 2014), known as cross-sectional geometric properties (CSGs), based on the area inside the bone (often divided into cortical area and medullary area) and distribution of bone around various planes. These will be discussed in greater detail in section 7.4. Finding these properties requires as accurate an image as possible of both the outer and inner shape of the bone. Various methods to analyse bone shape have been utilised over the last three decades, including x-rays, computed tomography, plaster casting, and most recently, 3-dimensional laser scanning. CT scanning is the “gold standard” as it effectively shows both external (periosteal) and internal (endosteal) shape, and is second only to physical sectioning of the bones, which is impossible in many studies as it is irreversibly destructive. The research presented here primarily relies on the analysis of external shaft shape, with thickness of the bones of secondary importance. CT scanning is both expensive and requires transport of bones to an external scanning facility or hospital, which many researchers in museums or in the field are unable to do.

Fortunately, many researchers have faced similar problems and have developed a variety of solutions. Biplanar x-rays, sometimes referred to as the "ellipse model method" or EMM, involves taking two radiographs, one from the mediolateral aspect and one from the anteroposterior aspect (Runestad *et al.* 1993). These are then measured and calculated as if the bone were a hollow ellipse. The method with which EMM is often used is the plaster or latex casting method (LCM or PM), which uses a cast to show the external shape of the shaft. On a test of femurs, O'Neill and Ruff (2004) found that for cortical area, LCM had an error rate of 4-9% and EMM 7-16% when compared to either direct sections or scanned photographs of "fortuitous breaks". Error was similar for other biomechanical properties. EMM was found to have a strong correlation with results from sections when its bias towards overestimation is corrected. However, LCM is not approved by some conservators as it can adhere to and damage fragile bone.

The most recent technological innovation to be used for this type of biomechanics research is the 3D laser scanner (Kuzminsky and Gardiner 2012; Davies *et al.* 2012). As with many archaeological techniques, the 3D scanner was developed for engineering purposes. Instead of creating a physical cast of the bone which must then be scanned into the computer (Ruff and Hayes 1983; O'Neill and Ruff 2004), the 3D scanner inputs the bone shape directly into the computer using x-, y-, and z-coordinates, so there is less chance of material or user error when inputting data. The 3D scanner is non-invasive and non-destructive and can give a clear picture of the tibial outline in a relatively short time (high-definition scans take about 20 minutes per bone). The scanner uses two parts: the device and the object support, which is composed of a rotating platform and a vertical bar. The platform is covered in rubber, and the vertical bar holds the bone in place with a rubber grip, preventing any accidental scratching. If the bone appears to be unstable on the platform, it can be further supported with a foam support, so there is no risk of any damage to the bone. In a recent study comparing laser scanning with LCM, CSG properties were found to be highly correlated between methods with a low rate of error (Davies *et al.* 2012).

To complement the coordinate data obtained through 3D laser scanning, Davies wrote a program, AsciiSection (see Section 7.3.1 below), that interprets the data in biomechanical terms; it is possible to input a location (in percent) on the bone for which data is needed, and receive it instantly. This is much more efficient than casting, wherein one needs to make a wholly different model for each location along the shaft, and allows for much greater specificity. The only problem with 3D laser scanning is the same as the major problem with LCM, which is that it overestimates the medullary cavity, which has a knock-on effect for measuring the cortical area as a percent of the total area. Some research indicates (Cooper *et al.* 2008) that the endosteal area may be critical for understanding bone growth and loss; as an individual ages, the periosteal shape may not change, but the individual may lose bone density and bone from the medullary cavity. Clinical studies using CT scans have shown that increased activity adds bone to the periosteum in youth and reduces endocortical loss in old age (Perreard Lopreno 2016). Sarringhaus *et al.* (2005) first explored CSG using only the subperiosteal area. Sparacello and Pearson (2010) found that the periosteal contour alone provides an accurate estimation of biomechanical properties unless one is looking at senescence or individual values, a result evinced by Stock and Shaw (2007), and Macintosh *et al.* (2013) found that only CSG properties near the very proximal and distal ends were significantly different. Considering the average age at death was low for the assemblages being assessed (based on prior analysis of some of the material, age-at-death for most adults is within the 20-25 or 35-50 categories) and the difficulty in reliably aging any of the individuals, it was arguably not worth taking radiographs for the marginal difference they may have made to the estimation of cortical area. As 3D laser scanning is unable to differentiate between cortical area and medullary area, only total area (the combination of the two) was considered in this study.

7.3.1 NextEngine™ 3D Scanner

This project uses UCL Institute of Archaeology's NextEngine™ 3D laser scanner, which uses structured light scanning. Triangulation between laser projection stripes enables the scanner to calculate the distance between points and produce a 3D model (White 2015). The scanner consists of two parts: the scanning device, containing the lasers, which is

8.8x3.6x10.9 inches, and the rotating AutoDrive™ table with extendable PartGripper™ arm to hold the object. The rubber grips, as mentioned above, prevent any accidental scratching. The tibia was installed on the AutoDrive™ longitudinally in anatomical position, beginning with the proximal end upright. Foam pads were used to stabilise the distal end. The AutoDrive™ plugs into the scanning device at a maximum distance of 17 inches. After plugging in the device and connecting it to a laptop running NextEngine™'s RapidWorks ScanStudio HD, the bone was scanned and saved.

Testing of the NextEngine™ revealed that specific steps must be taken for usable results from human bone. First, a dark background (created with black foam boards) improved contrast considerably. Shorter and longer distances were tested; 17 inches produced the clearest results. After testing the various scan settings in ScanStudio, the 19-minute 360° 11-part scan (that is, the AutoDrive™ rotates 11 times) produced the highest quality scan. Still, the scanner's field of vision was too narrow to capture the complete length of many bones at the best distance for contrast, thus longer tibias needed to be flipped upside down (with the proximal end facing downwards) and re-scanned, with appropriate conservation-approved adhesive labels to ensure accuracy in alignment. The images of the proximal and distal halves were then aligned and digitally stitched together. The entire process, including setting up and taking down the bone, took approximately 40 minutes and resulted in a .scn file containing a virtual image of the bone as well as a .xyz file, readable in other programs. Five individuals were scanned twice on different days to ensure calibration of the scanner and replicability of the AsciiSection program, discussed below. Additional individuals were scanned, but a fault in the scans due to user error rendered them unusable for this study due to irregular or shaky outlines and thus unreliable CSG properties (the scanner was susceptible to interference due to small vibrations – footsteps, door slams – and these could not be known until the program was run after data collection was complete).

7.3.2 AsciiSection

Davies' program for interpreting 3D scanned images is called AsciiSection. The program exports all x-, y-, and z-coordinates and transforms them into 2-dimensional outlines of the shaft shape at slice thicknesses set by the user (Davies *et al.* 2012), allowing for visual comparison and measurement in imaging programs such as ImageJ or its plugin for osteometric analysis, BoneJ. It is possible to compare results to CT scan data in DICOM format, although that was not done in this study.

7.4 Interpreting and analysing cross-sectional geometry

This section discusses the background of using cross-sectional geometry in long bone biomechanical analysis before describing the specific properties used in this study, including how they were obtained and how they will be analyzed.

7.4.1 Background

Many terms have both a common use and a specific quantitative use. Recall that stress and strain are units of measurement. Stress, identified as **σ** (sigma), is the applied force per unit area, measured in pascals. Strain, identified as **ε** (epsilon), is the relative change in size in a prescribed direction (Nigg *et al.* 2000): that is, deformation divided by the object's original length. Strain is expressed as deformation/length or as a percent and is dimensionless. Stiffness is the ratio of stress to strain in a loaded material (Hall 2014: 522). However, when bone stress and strain are discussed, the authors are referring to general stress and strain rather than specifically measured strain like that shown in Table 2.5.2. Likewise, strength, rigidity, and robusticity are also specific quantitative terms discussed further in this paper.

The first measurement relevant to this study is total area (**TA**). This is the total amount of area inside a transverse cross-section of a bone, expressed in mm^2. Alongside TA are cortical area (CA), calculated as TA-MA for gross amount and CA/TA for percentage, and medullary area (MA), calculated as TA-CA for gross amount or MA/TA for percentage, shown in Figure 7.4.1. Whether CA and MA are measurable depends on the type of analysis being conducted. With direct sectioning of archaeological remains or CT scanning of live individuals, CA and MA can be assessed. 3D scanning only examines the surface of the bone: thus only TA can be measured, as discussed above.

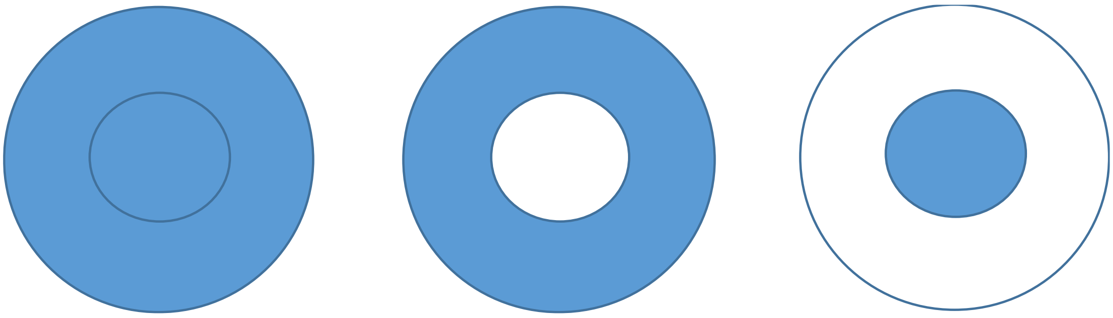


Figure 7.4.1 Illustration of hollow circular cross-sections demonstrating the difference between TA (left), CA (centre), and MA (right). S. Hackner 2016.

Further units of measurement are called *moments*. A moment is a turning effect of a force around an axis (Nigg *et al.* 2000), and there are a number of moments that can be recorded and compared. The second moment of area describes the distribution of mass within an area (such as a bone), and is that bone's resistance to rotational acceleration and bending loads (Nigg *et al.* 2000; Stock *et al.* 2011). It is based on both mass and the distribution of that mass around an axis of rotation, or centroid. Second moments of area are also called moments of inertia and are expressed as $\boldsymbol{I}$ (Ruff 2000: 274; Hall 2012: 450). Second moments of area can be calculated using various formulas if the mass, radius, and distribution of mass are known (Hall 2012), but for the purpose of this project they are automatically calculated using AsciiSection, a program described in this chapter and used to create cross-sections of 3D scans. I can be calculated for numerous axes, of which four are commonly used. **I_x and I_y** are the moments of inertia in the x and y plane, and **I_{max} and I_{min}** are the moments of inertia in the maximum and minimum planes. The angle between I_{max} and I_x, shown in Figure 7.4.2, is expressed as θ (theta), showing bone torsion (Wescott *et al.* 2014). This demonstrates the rotation of the bone in relation to the primary axes of the body (C. Ruff 2008). These second moments of area can result in a shape ratio, calculated as I_{max}/I_{min} (about the maximum and minimum axes) or I_x/I_y (about the mediolateral and anteroposterior axes), expressed in mm^4; the closer to 1.0, the more circular the cross-section (Macintosh *et al.* 2014: 380).

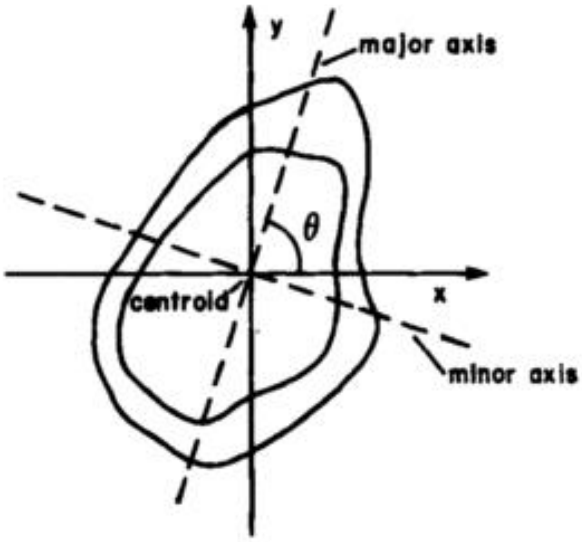


Figure 7.4.2 Illustration of tibial cross-section showing maximum and minimum axes and anteroposterior and mediolateral axes and θ. As taken from Ruff and Hayes (1983a: 360).

The second moments of area can be added to produce ***J***, the polar second moment of area. *J* (I_{max}+I_{min}) is the torsional or twice bending rigidity of any two perpendicular planes. Here, rigidity is defined as the ability to resist deformation, expressed as *J* (Stock *et al.* 2011: 352; Ruff 2008: 185). *J* has been found to correlate with TA, but has also been shown to be less accurate in noncircular sections: thus *J* is a better metric for measuring torsional rigidity in the femur than in the tibia (Ruff and Hayes 1983: 361; Lieberman *et al.* 2004: 169). *J* increases from the distal end to the proximal end of the tibia, which reflects both the expansion and the decreasing circularity of the tibia and becomes an overestimate (Ruff and Hayes 1983: 369). All of these CSG properties are shown in Table 7.5.3 for ease of reference.

Term	**Abbreviation**	**Formula**
Total Area	**TA**	-
Cortical Area	CA	TA-MA
Medullary Area	MA	TA-CA
2nd moment of area around AP axis	I_y	-
2nd moment of area around ML axis	I_x	-

2nd moment of area around greatest axis	I_{max}	-
2nd moment of area around least axis	I_{min}	-
Polar 2nd moment of area	**J**	$I_{max}+ I_{min}$
Shape index in greatest/least plane	-	**I_{max}/I_{min}**
Shape index in x/y plane	-	**I_x/I_y**
Angle between greatest plane and mediolateral plane	θ	-

Table 7.4.3 Units in cross-sectional geometry, summarised from Macintosh *et al.* (2014); Ruff (2008); and Stock and Shaw (2007). The units shown in bold are those examined in this study.

7.4.2 Cross-sectional geometric properties used in this study

Using AsciiSection to extract values, this study examines and compares the following CSG properties which are used as proxies for diaphyseal shape, explained fully above (after Stock and Shaw 2007; C. B. Ruff 2008):

- Total area (TA)
- Second moments of area ratios (I_{max}/I_{min} and I_x/I_y)
- Polar second moment of area (J)

For sexual dimorphism, the log of each non-ratio value is taken to ensure normal distribution; in the event that the values are normally distributed, the true values and not the log-transformed values are used.

As TA and J are dependent on body size, these measurements were then standardised using the following formulae, used by Macintosh *et al.* (2014) and Ruff (2008: 188):

StTA = TA/estimated body mass

StJ = *J*/(estimated body mass * (tibial intercondylar length)^2)

Standardised J was then multiplied by 10000 to facilitate analysis of the results (Alison Macintosh *pers. comm.*).

7.5 Geometric morphometrics

This section will cover the field of geometric morphometrics (GMM) and its applicability to the study of human remains and ancient activity before describing the two ways GMM is utilised in this study.

7.5.1 Background

How does one measure the mean of a set of shapes? What is their variability? Geometric morphometrics (GMM) applies mathematical and statistical methods to these questions (Brown 1994). Simply defined, traditional morphometrics is a quantitative measure of morphological traits. It categorises morphology in terms of lineal measurements such as lengths, angles, and ratios, which can be seen to some extent in the biomechanical research presented in Chapter 3. Geometric morphometrics is the quantitative representation of morphological shape using Cartesian coordinates instead of measurements, allowing researchers to directly compare shape without the additional factor of size by rescaling (Polly 2012). GMM data is easy to collect from photographs, CT scans, and 3D scans, and data is easy to present as figures instead of tables of numbers. Slice *et al.* (2007) point out that the "geometry" indicated in the name is *shape space*: the methods used in geometric morphometrics allow researchers to find and compare mean shapes and describe variation within a sample both mathematically and figuratively. Shape space here refers to Kendall's shape space, discussed below.

Geometric morphometrics has an extensive history in biology and zoology. It was first called "mathematical biology" and was utilised by D'Arcy Thompson in the early 1900s. His seminal work applied a coordinate grid to various zoological comparisons, particularly marine shells, and then applied further mathematical formulae to calculate differences in shape (Thompson 1948; Milnor 2010a), shown in Figure 7.5.1. He also addressed many issues inherent in scaling and conformal mapping, illustrating why (for example) a deer scaled up to the size of a giraffe could not support its own weight, solving the problem of comparing small and large animals (Milnor 2010b). Roughly concurrently, Francis Galton was developing similar methods with applications in criminology and anthropometry, resulting in fingerprint analysis (Polly 2012). The field stalled somewhat until the 1970s, when computer analysis finally enabled truly quantitative comparisons to be made, and was revived by Fred Bookstein and colleagues.

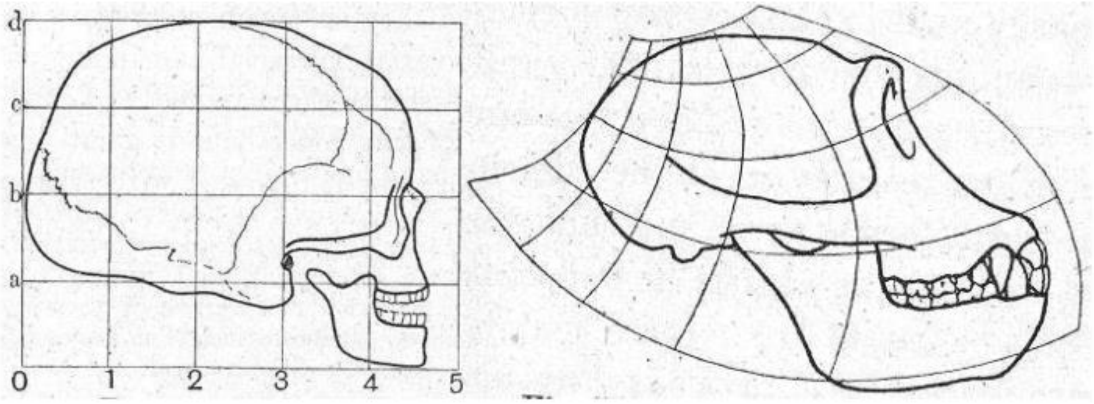


Figure 7.5.1 Thompson's coordinate plan comparison of a human and a chimpanzee skull. As taken from Milnor (2010b).

Geometric morphometrics in a 2D plane relies on the use of landmarks and outlines. Landmarks are coordinate points used to make a shape. They should be stable throughout the sample and easily identifiable, and thus are placed on areas that are biologically homologous such as those defined on the skull, tips or cusps of teeth, or endpoints. At least 3 landmarks are required in any analysis, illustrated in Figure 7.5.2. These can be combined to form the outline of a shape through Fourier analysis, which describes curve contours (Elewa 2010). To create a more accurate outline, semi-landmarks can be added: these are algorithmically (and arbitrarily) placed points between landmarks.

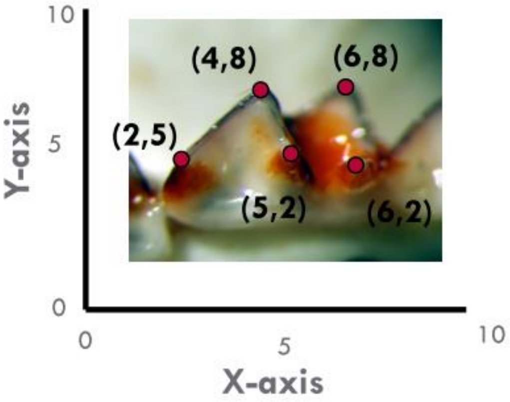


Figure 7.5.2 Three landmarks on teeth shown on a coordinate plane. As taken from Polly (2012).

Plotting shapes relies on first defining what a shape is. The shape of an object should remain the same no matter the angle of observation or if it is moved, rotated, enlarged, or reduced (Bookstein 1997; MacLeod 2016b). Bookstein remarks that when working with a group of point sets, it is more useful to define their shape as “the set of all point sets that have the same shape” (Bookstein 1997: 227), that is, as an equivalence class. However, for direct comparisons and averaging, techniques called Procrustes methods must be utilised. These are humorously named for the innkeeper of Greek mythology who would stretch or amputate victims to fit into the inn’s bed. Procrustes distance is defined as the square root of the sum of squared differences between the positions of the landmarks in two superimposed configurations (Slice *et al.* 2007: 20). Simply defined, it equates the distances between points in a shape. This is the basis of Kendall’s shape space, which is the fundamental geometric construction within geometric morphometrics (Slice *et al.* 2007: 13). Kendall’s shape space is a complex plane in which rotation, translation, and scaling have been removed as factors in determining an object’s coordinates: this is the base definition of a recognizable shape. In an example given by MacLeod (2016a), the object pictured in Figure 7.5.3 is recognizably Tower Bridge despite being rotated, rescaled, and in a place that is not normally associated with Tower Bridge – that is, in this document.

Figure 7.5.3 Is this Tower Bridge? After Macleod (2016b). Image courtesy Wikimedia Commons.

Geometric morphometrics used in biology allows researchers to address questions of convergent evolution, individual and species-wide growth and development, and plasticity of shape due to environmental factors or therapeutic interventions (Bookstein 1986; Brown 1994).

7.5.2 Geometric morphometrics in archaeology

Morphometrics has only recently been applied to archaeology. David Kendall, for whom Kendall's shape space is named, applied geometric morphometrics to alignments of standing stones, a subfield known as archaeoastronomy. This was actually a strict statistical application exploring the probability that Stonehenge's alignment was accidental (Brown 1994), but shows the possibilities of the field's applications.

Since the mid-2000s, geometric morphometrics has been utilised to examine shape differences in non-biological archaeological artifacts. Forel *et al.* (2009) used geometric morphometric analysis to determine intra-group variability of Bronze Age palstaves in an age where two centres of mass production had emerged, the Breton and the Norman. After cataloguing variability within these groups, the researchers analysed a third hoard which indicated additional production centres due to the shape variability within the sample, but that these outside production centres still based their work on the Norman/Breton models (Forel *et al.* 2009: 727).

Wilczek *et al.* (2014) compared ceramics that were analysed through geometric morphometrics to traditional typological methods. They noted that traditional typology may be affected by "operator subjectivity" (Wilczek *et al.* 2014: 39) owing to different levels of training and specialization, which is also a problem with certain bioarchaeological methods discussed in section 7.1. Their work used principal component analysis to examine differences between pots from a Second Iron Age Celtic site in France.

Geometric morphometrics has also recently been reapplied to the field from which it originated – anatomy and evolutionary studies. With 3D scanning in use as well as CT scanning and photogrammetry, there are a number of research projects investigating how these technologies can be combined with geometric morphometrics (or traditional morphometrics) to track biologically significant changes over time or between groups. Of course, the programs used in GMM such as tpsDIG and PAST3 were developed for multiple purposes (shells, rocks, palstaves) and their use for human remains is fairly new. A recent study by Wilson and Humphrey (2015) investigated asymmetry in Andaman Islander humeri by comparing second moments of area (discussed above) and GMM outline analysis. They used landmark analysis of 16 points on the external shaft, and like this study, discounted the medullary cavity as they also used a 3D scanner. For the small sample analysed, the authors found a significant relationship between both I_{max}/I_{min} and I_x/I_y and the first three principal components using a MANOVA ($r^2=0.25$, $F_{3,36}=13.98$, $p<0.0001$). The significance varied at different points tested along the shaft, particularly with regard to I_x/I_y, indicating that variation occurred in the mediolateral axis; additionally, differences in I_{max}/I_{min} aligned with the second principal component, showing that orientation of the maximum and minimum axes differs between points along the humeral shaft (Wilson and Humphrey 2015: 549).

7.5.3 Geometric morphometrics used in this study

In geometric morphometrics, a landmark refers to a “point that can be placed on a biologically or geometrically homologous point on the structure” (Polly 2012) and a semi-landmark is an arbitrarily or algorithm-derived point between these landmarks. For the 2D tibial section analysis, these are quantified as (x,y) coordinates on a traditional Cartesian plane (Slice *et al.* 2007).

For the pilot study, a number of landmarks and semi-landmarks were tested, ranging in number from 4 to 24, with 1 always at the most anterior point of the crest, using Morphologika v2.5. Ultimately, 6 points (3 landmarks and 3 semi-landmarks) were chosen (Figure 7.5.4) as they yielded the results most reflective of differences in the bone shape. The three landmark points are the anterior crest, the most laterally projecting point, and the most medially projecting point or edge; the semi-landmarks are 50% of the distance between each of these, mathematically determined using the ImageJ measurement tool. The three landmarks are homologous in each tibia and are also used for measuring by hand.

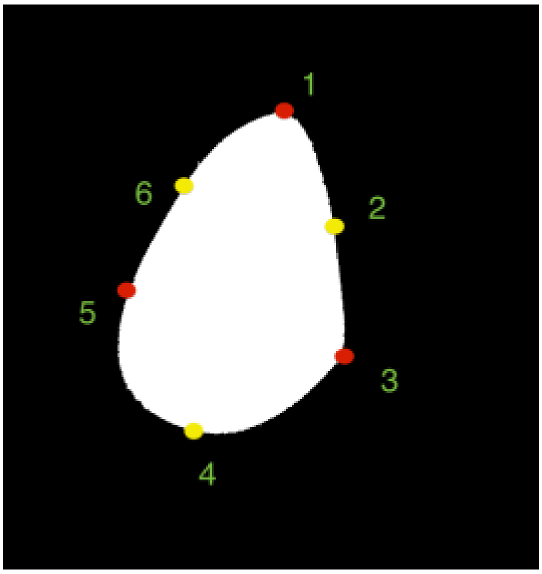


Figure 7.5.4 A tibial midshaft section showing the 6 landmarks and semi-landmarks selected; this is an illustrative example and the points shown are not in the exact places calculated. S. Hackner 2016.

All tibias were rotated or flipped for standardization with the interosseous border at the right of the image and the anterior crest at the top, shown in Figure 7.5.4. This does not affect the CSG properties or geometric morphometric assessments. Measurements of these points were taken in ImageJ and copied into a .txt file.

For the remainder of the post-pilot study, the entire outline of each scan was used. This was performed using the R statistical programming language with the Momocs package developed by Bonhomme *et al.* (2014). Momocs allows tibial cross-sectional scans to be directly input as .txt files: it then enables principal component analysis, described below, of the entire outline as well as automatically generating mean shapes, shown in Appendix II. These results are best shown graphically, as R enables customizable graphing to a much greater extent than Morphologika. Statistical tests including MANOVAs of shape categories and principal components were conducted in R and in SPSS.

7.6 Categorization of shape

As discussed in Chapter 4.1.2, categorization of diaphyseal shape has been practiced in anthropology but not specifically analysed from a mathematical or morphometric approach. This study aims to ascertain whether the shape categories described by Hrdlička have biological or archaeological relevance, and whether they can be associated with particular groups within the assemblages.

7.6.1 Shape categories

Each tibial cross-section from each site was printed and numbered. These were then divided into shape categories based on the results of the pilot study. While Hrdlicka's shape categories were used as a point of reference, they were not directly utilised to create the shape categories analysed here. The first iteration of this exercise required four osteologically-trained individuals (SH, RW, MB, EF) to sort the cross-sections with no instruction. From this, six categories emerged and were defined using points and sulci:

1. *Triangular*: the "typical" tibia shape, where three points are clearly visible at the anterior crest, lateral and medial sides, and are connected by flat or nearly flat sides (Hrdlička type I)
2. *Droplet*: a pointed anterior crest but rounded posterior edge and slightly convex medial and lateral sides. This shape tends to be the smallest (approximately Hrdlička type V)
3. *Flat side*: a pointed and lateral-leaning anterior crest, rounded posterior edge, convex medial side, and flat or faintly sulcated lateral side leading to a slightly pointed interosseous crest (Hrdlička type VI)
4. *Half-moon*: a pointed and lateral-leaning anterior crest, convex medial side, sulcus at lateral side, and flat or slightly rounded posterior edge (Hrdlička type III)
5. *Diamond*: four distinct points at the anterior crest, interosseous crest, medial edge, and posterior buttress (an elongation and point on the posterior side), with sulcus at lateral side and convex medial side (Hrdlička type IV)
6. *Elongated ovoid*: a nearly oval shape with a small but defined interosseous crest (no corresponding Hrdlička type)

Figure 7.7 shows these shapes flipped as discussed above and rotated with the anterior crest to the top for easier comparison.

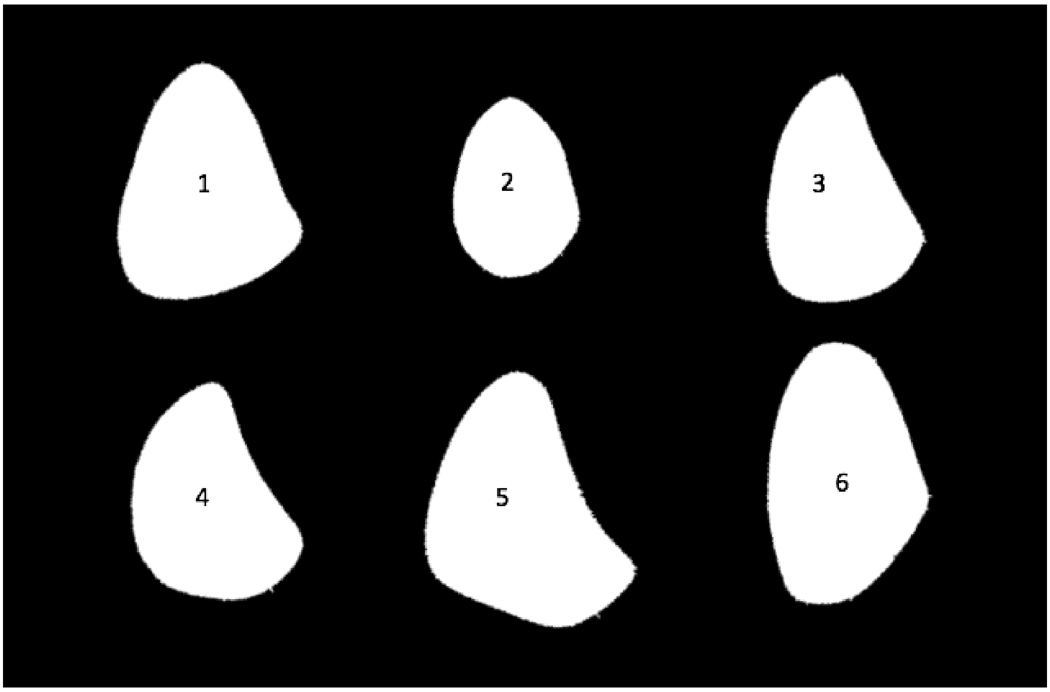


Figure 7.6 The six shape categories: 1=triangular; 2=droplet; 3=flat side; 4=half-moon; 5=diamond; 6=ovoid. Note the size difference, which is eliminated in the Procrustes analysis. S. Hackner 2016.

These same observers were next given the above definitions and an example of each category and asked to identify each shape. The observers were in agreement in over 90% of cases; rates of agreement using Cohen's kappa are given in section 7.8 (see table 7.8.14).

7.6.2 Principal component analysis

After rough shape analysis, the cross-sectional images were subjected to geometric morphometric analysis. In the pilot study, they were entered into Morphologika v2.5, and in the complete study, they were read into Momocs, where they were subjected to Procrustes analysis to normalise for size and angle and Principal Component Analysis to determine the areas of greatest variance within the data (Slice *et al.* 2007). Procrustes analysis is useful as it eliminates size as a variable. The scaled coordinates after the Procrustes change to reflect relative position only. As females at the examined sites are frequently smaller than males, it allows for true shape comparison. Morphologika produces a Procrustes Mean, or consensus shape, which can be interpreted as the figure with least distance to all samples (Slice *et al.* 2007).

7.7 Statistical analysis

All statistical tests were performed in IBM SPSS v24. Procrustes tests, which remove size as a factor in order to examine shape directly, and principal component analyses, which show the greatest differences in the shape variation, were performed in Morphologika v2.5 for the pilot study and R with Momocs for the complete study as it is a more powerful program. These are standard tests within geometric morphometrics to examine variation in shape (Bonhomme *et al.* 2014; MacLeod 2016). Statistical tests included parametric and non-parametric tests and were particular to the data being examined. To test for normal distribution, Shapiro-Wilk tests were used. The Shapiro-Wilk null hypothesis is that the data are normally distributed, and the limit for acceptance of the null hypothesis here is $p<0.005$. However, since normal distribution in a Shapiro-Wilk depends on sample size, the data are displayed using a normal quantile-quantile (Q-Q) plot to verify the distribution, as well as checking skewness and kurtosis (Field 2013). Distributions are also displayed as histograms. Correlations between categories (sex and shape, age and shape, robusticity and sex, robusticity and age, robusticity and shape) were tested using Pearson's correlation. In order to examine inter-site, inter-sex, and categorical differences, one-way and two-way analysis of variance (ANOVA) tests were conducted. These were followed by Levene's test for homogeneity of variance to assess the assumption that population variances are equal. Tukey's and Welch's post-hoc tests were applied when necessary for different groups based on the results of the Levene's test to control for experimentwise error rate (Laerd Statistics 2013; Field 2013). To test whether there were significant differences between principal components in site, sex, age, shape, and robusticity categories, multiple analysis of variance (MANOVA) tests were used. Independent *t*-tests were used to compare intra-population sexual dimorphism, and Wilcoxon signed-rank tests for asymmetry as used by Nikita *et al.* (2011), Trinkaus and Ruff (2012), and Macintosh *et al.* (2014). A Pearson chi-square was used to determine significance, with the limit for acceptance or rejection of the null hypothesis set at p=0.05. These tests are used based on type of data (categorical, numerical) and sample size and are comparable to statistical tests performed in similar archaeological analyses.

7.8 Pilot Study

Prior to the main data collection, a pilot study was conducted using tibiae from Jebel Moya and Naqada that aimed to establish whether the methods presented above in this chapter show differences between individuals within a group and between groups, and to test whether both legs of an individual need to be scanned to streamline the rest of the study. The pilot study was conducted in two stages:

The first stage focused on cross-sectional geometry (herein referred to as Part A) and compared 26 randomly-selected Jebel Moya individuals from the total scanned assemblage with 25 tibiae from Naqada, a predynastic Egyptian site, both part of the Duckworth Collection at the University of Cambridge. These tibiae were separated from the rest of the skeleton, therefore corresponding age and sex data for each individual based on pelvic ageing and sexing methods could not be determined. The selected tibiae from Jebel Moya and Naqada were used to compare cross-sectional geometric properties at midshaft. From the discussion outlined in Chapter 6.3, the literature identifies that people buried at Naqada were an agricultural group, whereas current interpretations identified Jebel Moya as a nomadic-pastoral group. This first phase of the pilot study presents a strict comparison of only tibiae, with no additional skeletal context as the Naqada tibiae were not associated with additional skeletal elements. Cross-sectional geometric properties (total area, anteroposterior and mediolateral second moments of area, maximum and minimum second moments of area, and torsional strength, discussed above) of the scans from both sites (n=51) were compared. If inter-site differences could be observed, it would be appropriate to add more sites to the analysis.

Secondly, a morphometric approach (herein referred to as Part B) was applied to the tibiae to explore sexual dimorphism within one site. This part only examined tibiae from Jebel Moya (n=67) as they had been assigned to sex categories. If intra-site differences could be seen with regard to sex and/or shape, it would be appropriate to continue morphometric analysis with other sites in the main study. Part B also explored whether directional asymmetry is present in this group and the implications for scanning left or right tibiae.

The pilot study addresses three main questions:

1. Using 3D scanning of the tibial midshaft, can a difference be seen between two skeletal collections that, according to the literature, practiced different subsistence strategies and thus different daily activities?
2. Can a difference be seen within the larger group between males and females? Is the rate of sexual dimorphism enough to justify considering them separately?
3. Is there enough asymmetry to justify scanning both tibiae of an individual? Does preservation allow scanning of both tibiae?

7.8.1 Measurements used in the pilot study

The default osteological method of examining tibial "shape" is a ratio derived from measurements of the anteroposterior and mediolateral diameters at the nutrient foramen or at midshaft (Bass 2004; see section 4.1.2). This ratio expresses the "flatness" of the tibia anteroposteriorly, which is similar to the descriptions of "shape" that use second moments of area as these also express distribution of bone around perpendicular axes rather than true cortical shape. As discussed in Chapter 2.4.1, the nutrient foramen has been shown to be an unreliable measurement as it varies in location (Dove *et al.* 2015; Hackner and Antoine 2016). When considering the midshaft measurements, the data from previous research show that size is strongly related to sex: males have larger tibiae overall and thus larger diameters, shown in Figures 7.8.1 and 7.8.2. The mean anteroposterior midshaft diameter in the Jebel Moya sample is 33.3 mm for males and 27.5 mm for females. The mean mediolateral midshaft diameter in the Jebel Moya sample is 23.7 mm for males and 20.5 mm for females; the average for each sex could not be determined for Naqada as they lack the skeletal context to determine sex and thus are marked here as ambiguous/undetermined.

This is typical of overall measurements of sexual dimorphism such as the femoral head diameter, discussed above, which is dimorphic enough to be used as a method of determining sex according to Bass (2004); however, there is some overlap between males and females. The tibial midshaft has not been investigated as a method of determining sex, and that is not the purpose of this investigation. Mediolateral and anteroposterior diameters appear to be not normally distributed: at Jebel Moya, mediolateral p=0.818 and anteroposterior p=0.22; at Naqada, mediolateral p=0.325 and anteroposterior p=0.254. However, the normal Q-Q plot for anteroposterior diameter, shown in Figure 7.8.3, shows alignment with the normal line: despite the high p-values, the distribution is not that far from normal, indicating that the results are not significantly rather than non-normally distributed. It is likely that the sample size used here is too small. Despite the small sample size, it is possible to see clustering of males and females from Jebel Moya. The Naqada individuals are not divided by sex, but tend to group around and below the Jebel Moya females. As they tend to be both shorter in length and smaller in diameter, this could indicate that the Naqada individuals are smaller overall than individuals from Jebel Moya, resulting in overlap of Naqada males and Jebel Moya females.

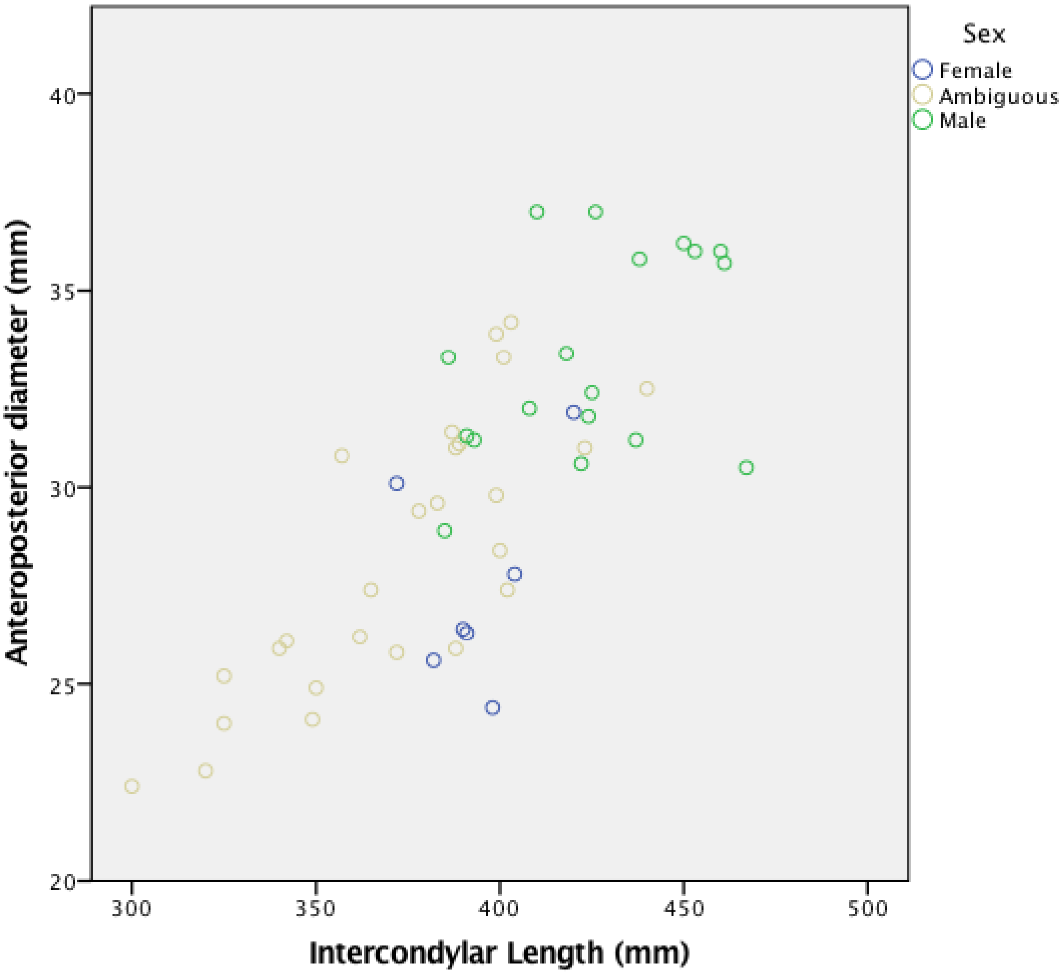


Figure 7.8.1 Tibial anteroposterior diameter at midshaft plotted against intercondylar length for Jebel Moya and Naqada. Coloured points separate the data by sex. The majority of ambiguous/unassigned (beige points) are from the Naqada sample; only 1 Jebel Moya individual in this sample is ambiguous/unassigned.

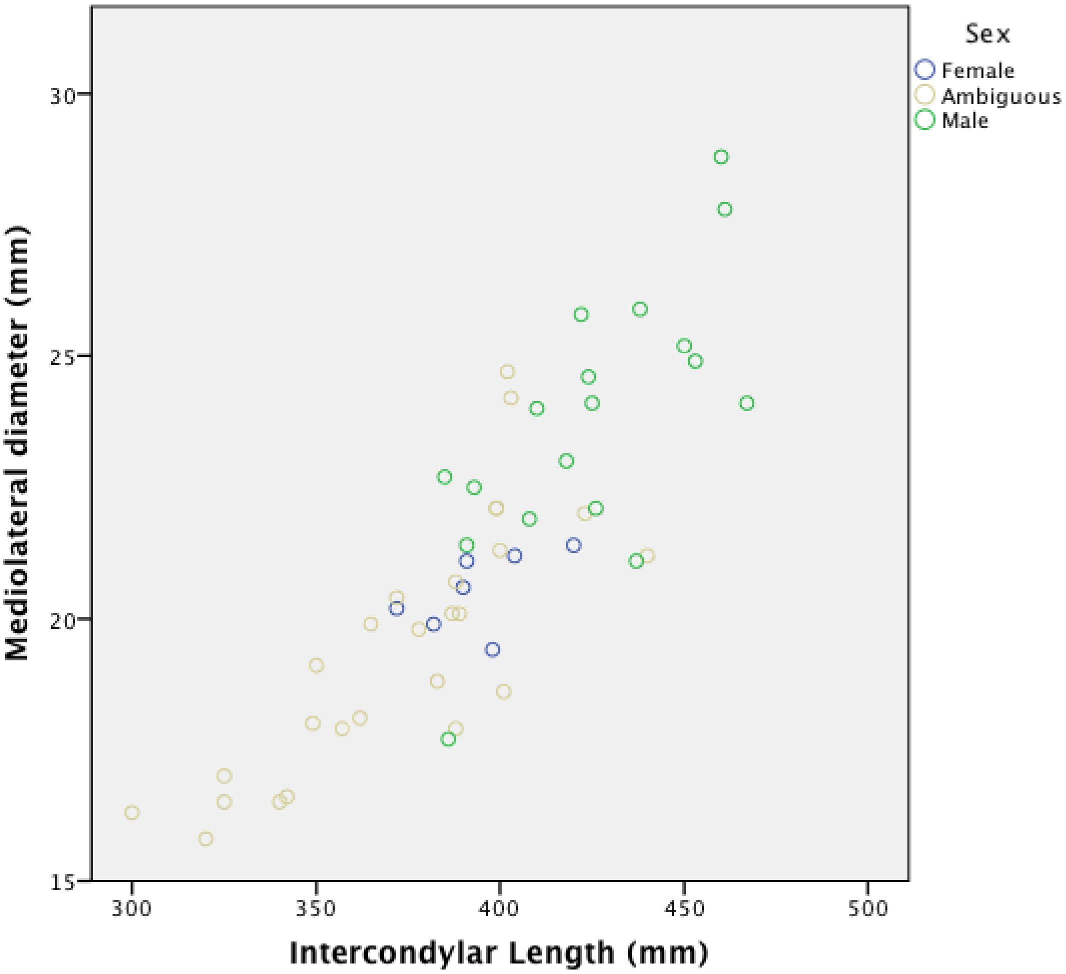


Figure 7.8.2 Tibial mediolateral diameter at midshaft plotted against intercondylar length for Jebel Moya and Naqada. Coloured points separate the data by sex. The majority of ambiguous/unassigned (beige points) are from the Naqada sample; only 1 Jebel Moya individual in this sample is ambiguous/unassigned.

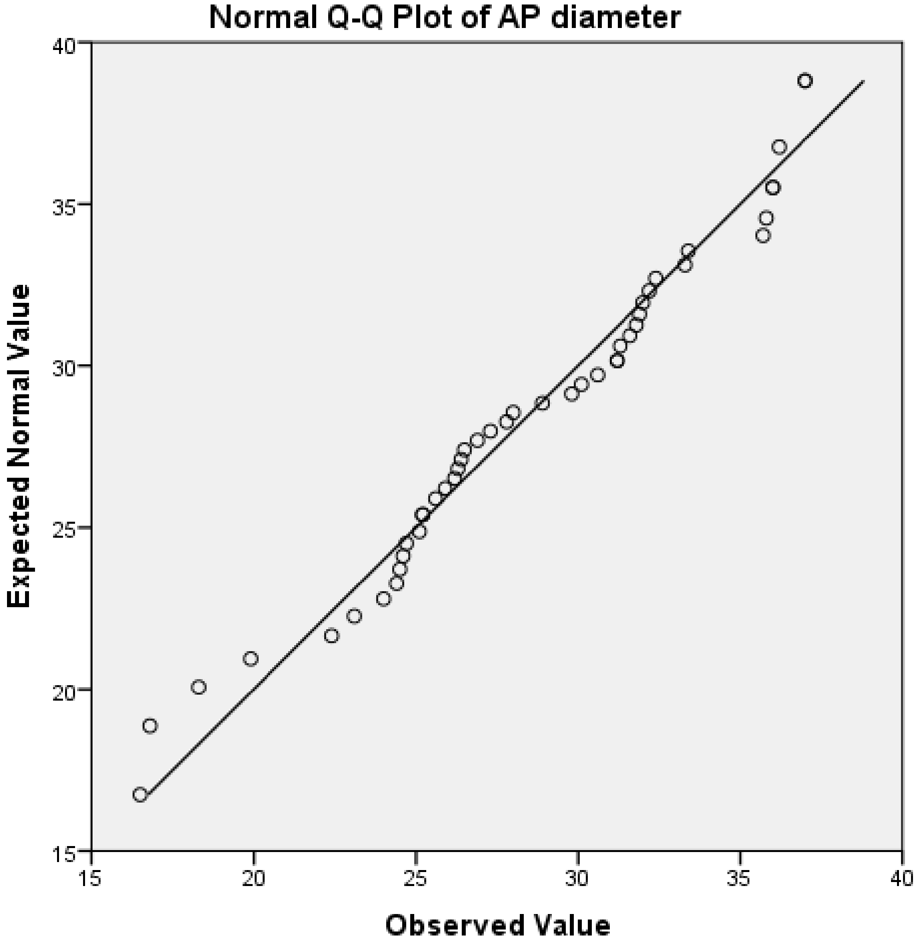


Figure 7.8.3 Normal Q-Q plot for tibial anteroposterior diameter at midshaft using the entire pilot study sample, showing a good fit to the normal line. The Q-Q plot for mediolateral diameter is nearly identical and is not shown here.

Length was also examined. A Q-Q plot using a Shapiro-Wilks test (Figure 7.8.2) shows that tibial intercondylar length at each site is normally distributed (at Jebel Moya p=0.316, at Naqada p=0.831), shown in Figure 7.8.4.

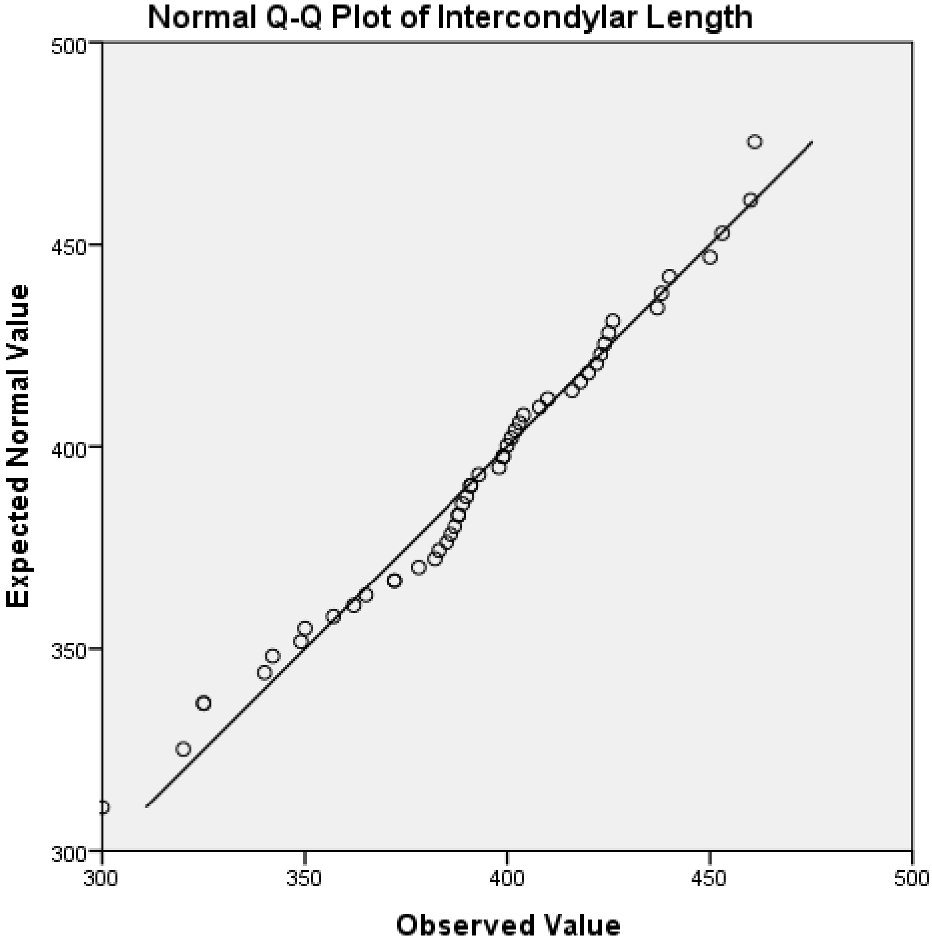


Figure 7.8.4 Normal Q-Q plot for tibial intercondylar length using the pilot study sample. The distribution shows a good fit to the normal line.

7.8.2 Part A: Results of cross-sectional geometric properties

Shapiro-Wilk tests for normality were conducted as the sample size is small. Significance for all CSG values are as follows: TA at Jebel Moya p=0.297, at Naqada p=0.343; I_{max}/I_{min} at Jebel Moya p<0.001, at Naqada p=0.326; I_x/I_y at Jebel Moya p=0.829, at Naqada p=0.81; J at Jebel Moya p=0.077, at Naqada p=0.147. The only non-normal distribution in the sample is Jebel Moya's I_{max}/I_{min}, possibly due to the presence of an outlier. Normal Q-Q plots are shown in Figures 7.8.5 and 7.8.6.

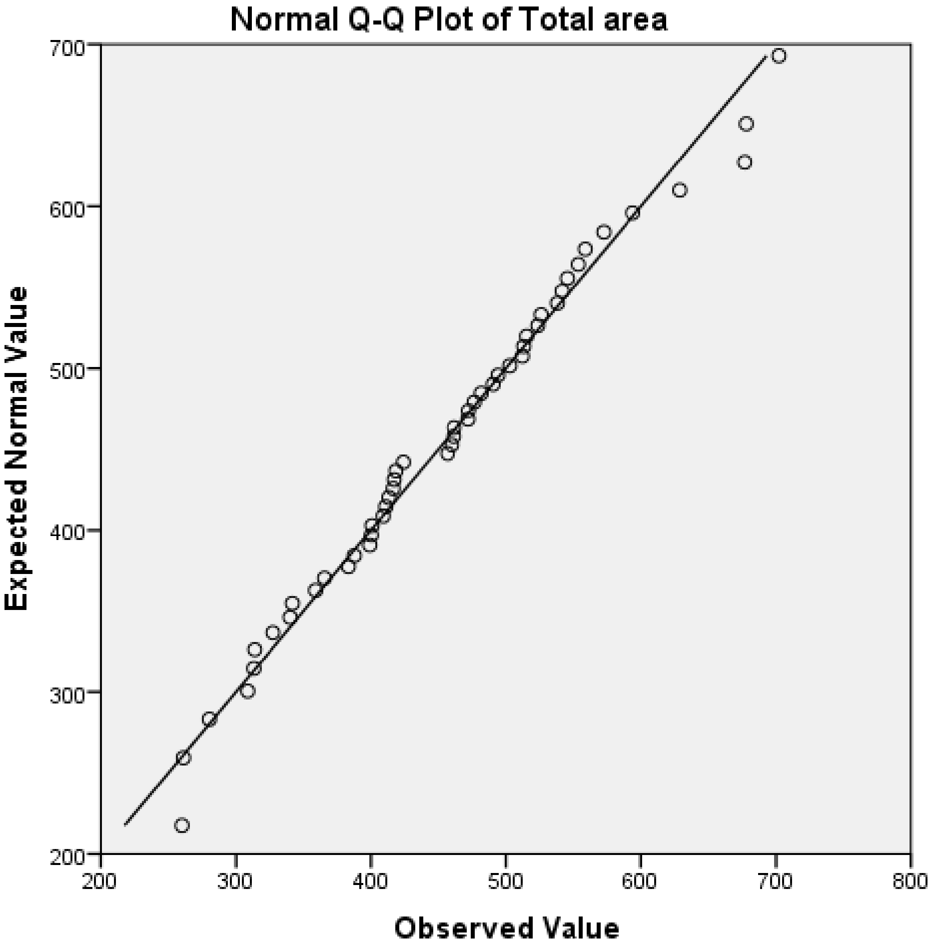


Figure 7.8.5 Normal Q-Q plot for tibial TA at midshaft using the pilot study sample. The distribution shows a good fit to the normal line.

For I_{max}/I_{min}, Naqada was normally distributed (p=0.326) but Jebel Moya was not (p<0.001), possibly due to the presence of an outlier at the higher end, shown in Figure 7.8.6.

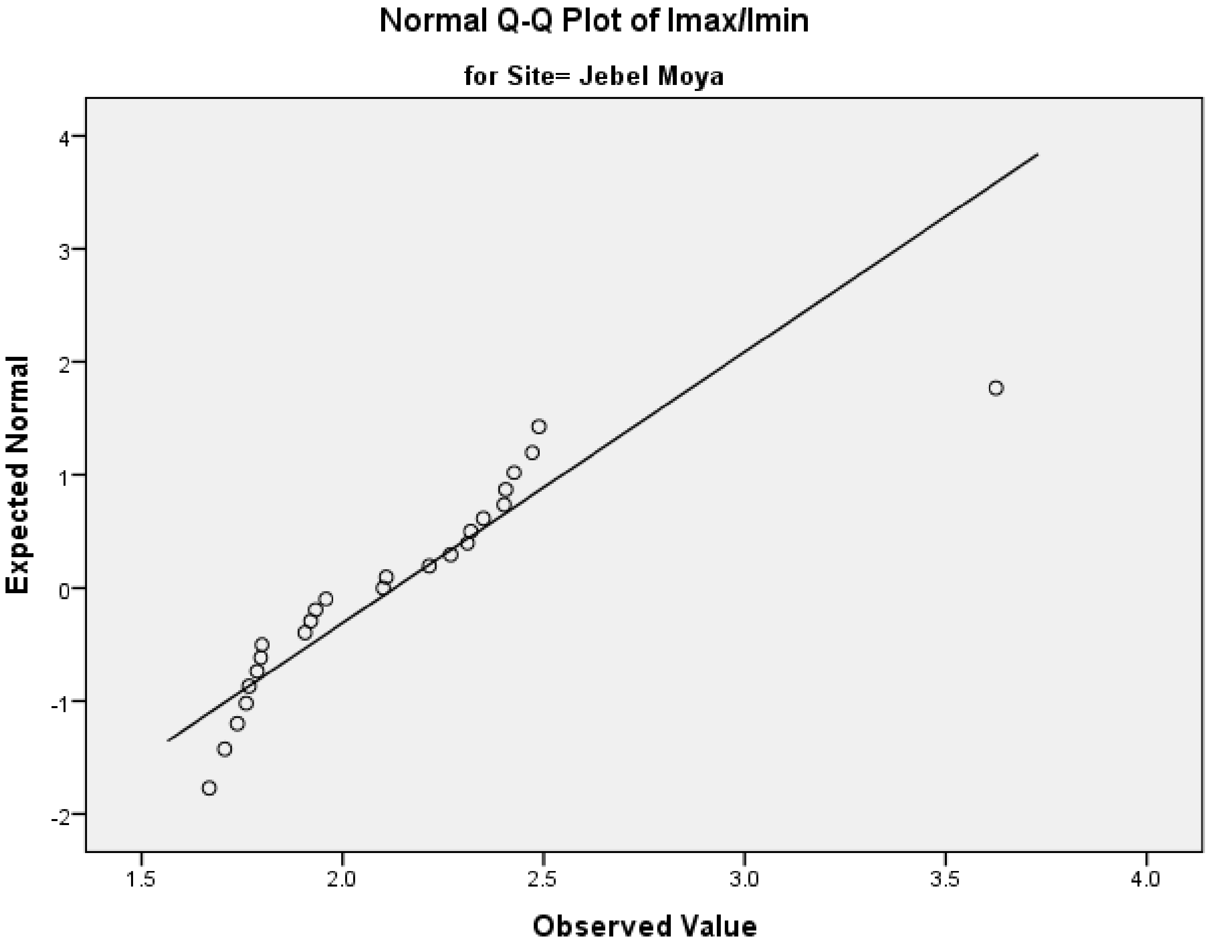


Figure 7.8.6 Normal Q-Q plot for tibial I_{max}/I_{min} at midshaft using the Jebel Moya pilot study sample. Significance is p<0.001. Naqada is not shown in this plot.

I_x/I_y was normally distributed (Jebel Moya p=0.821, Naqada p=0.081), as was J (Jebel Moya p=0.077, Naqada p=0.147).

The results of tests for cross-sectional geometric properties are shown in the figures below. The TA and length of Naqada tibiae are both lower than those of Jebel Moya tibiae, shown in Figure 7.8.7. At Naqada, intercondylar length ranged from 300mm-440mm (mean 371.52mm, SD=34.29), and at Jebel Moya 372mm-461mm (mean 413mm, SD=25.18); at Naqada, TA ranged from 259.99 mm^2-558.676 (mean 400.774 mm^2, SD=89.855), and at

Jebel Moya 365.603 mm^2-702.065 mm^2 (mean 509.63 mm^2, SD=93.634). TA could not be standardised as the Naqada tibiae are not associated with femora, so both remain as original TA calculations; standardization by length produced nearly identical results. Using a paired-samples t-test, length and TA are found to be correlated ($p<0.001$ at both sites). Figure 7.8.8 shows length compared to I_{max}/I_{min} and Figure 7.8.9 shows length plotted against I_x/I_y: neither second moment of area ratio is correlated with length. Figure 7.8.10 shows length plotted against J; as with TA, there is a correlation, and Jebel Moya tibiae displays higher J values.

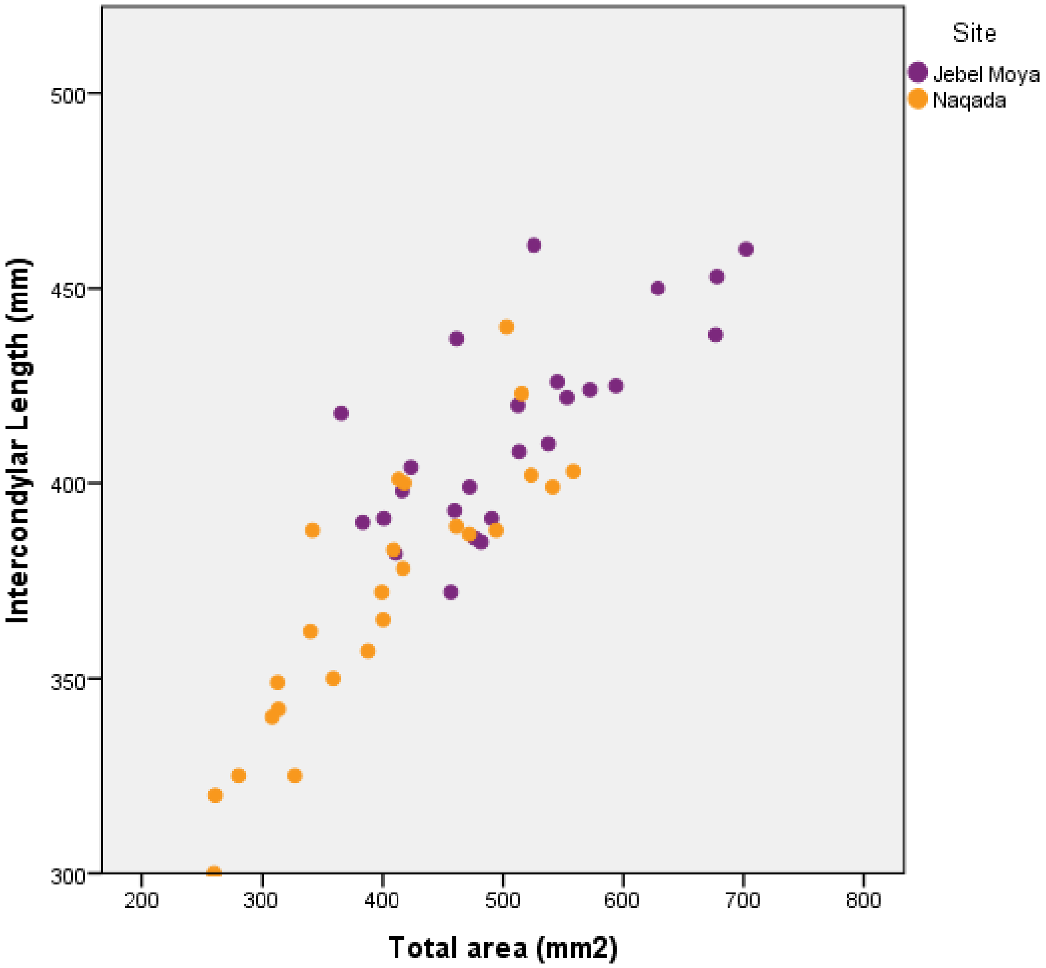


Figure 7.8.7 Total area (mm^2) plotted against length (mm) at Jebel Moya and Naqada ($p<0.001$ at both sites), indicating correlation between these variables.

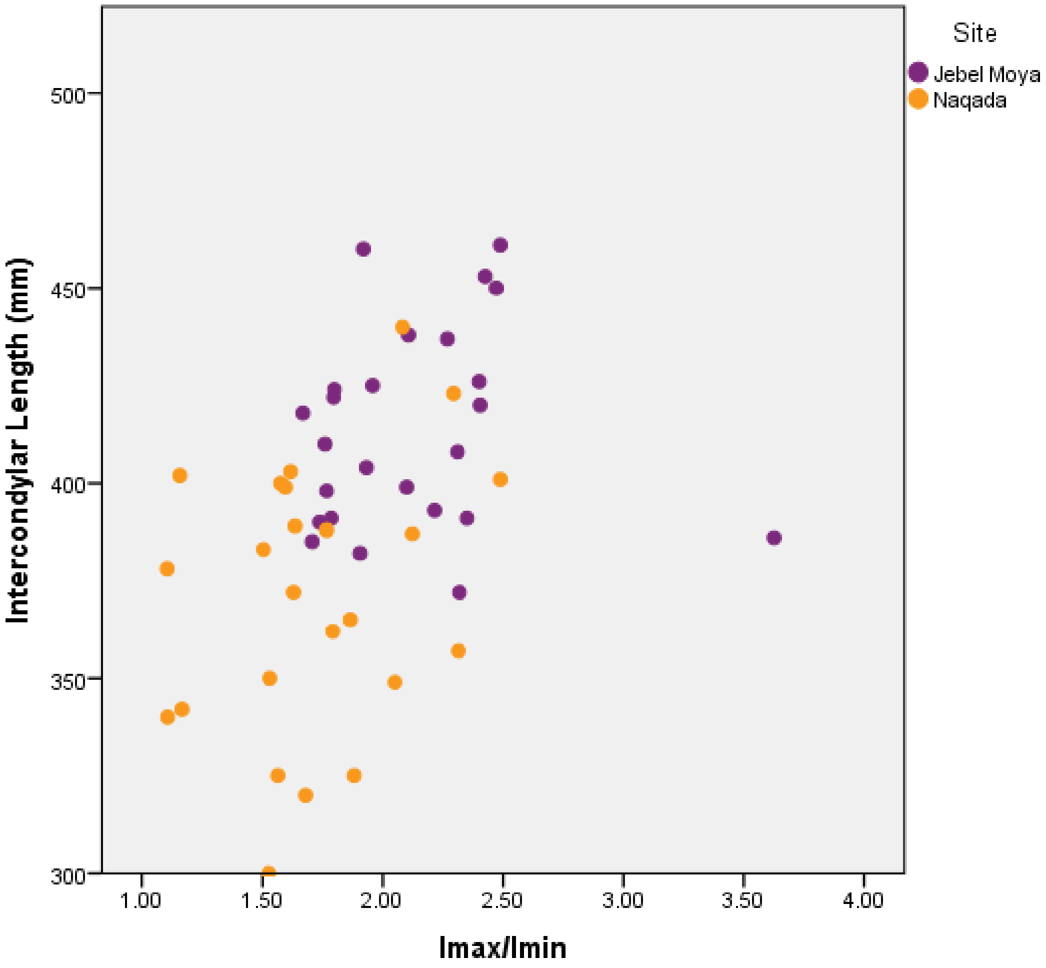


Figure 7.8.8 I_{max}/I_{min} plotted against intercondylar length (mm) at Jebel Moya (p=0.745) and Naqada (p=0.171), indicating no correlation between these variables.

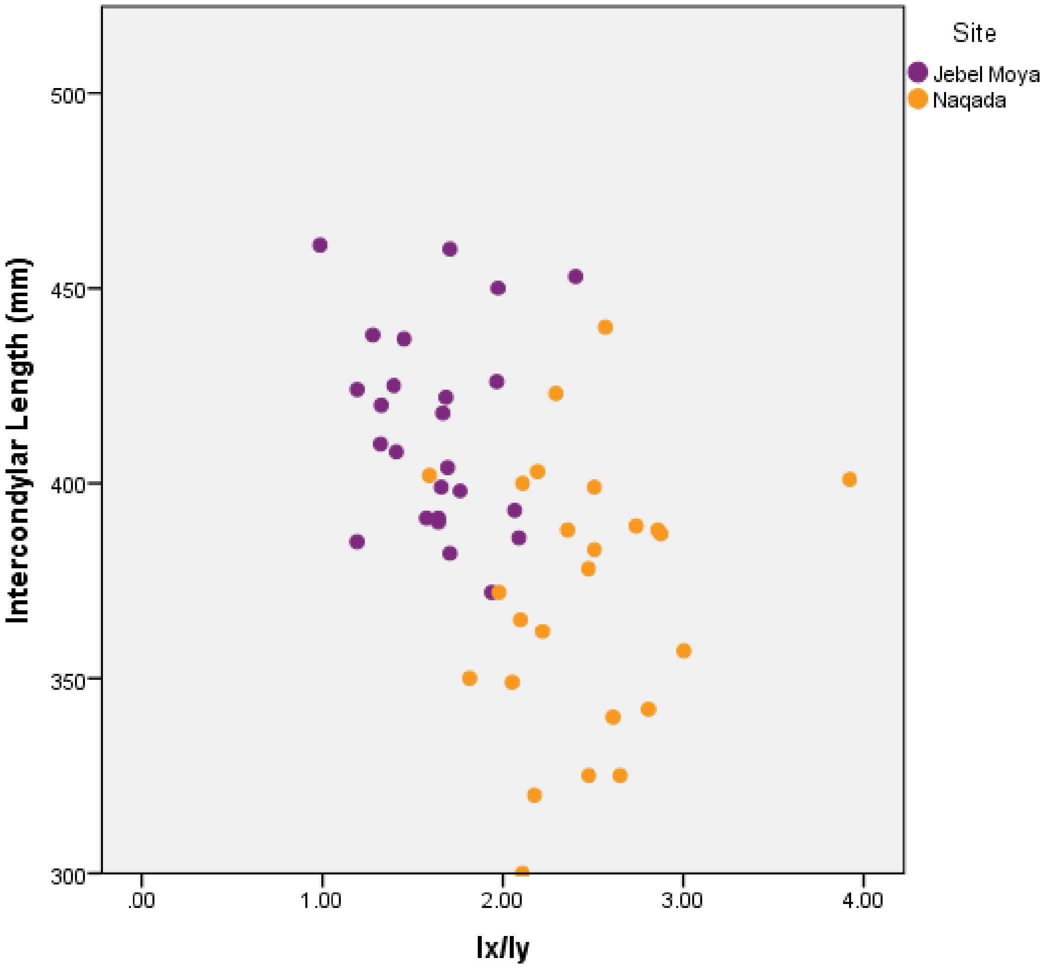


Figure 7.8.9 I_x/I_y plotted against intercondylar length (mm) at Jebel Moya (p=0.55) and Naqada (p=0.533), indicating no correlation between these variables.

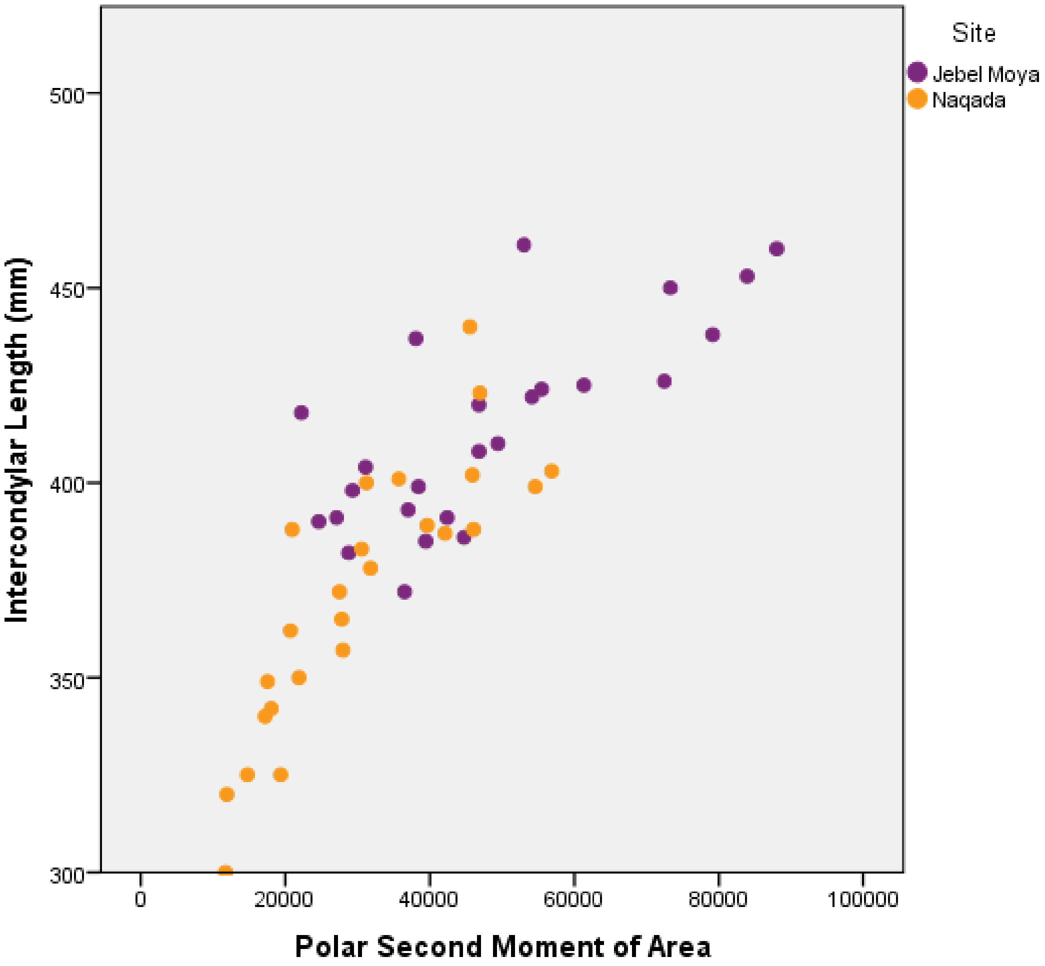


Figure 7.8.10 Polar second moment of area (*J*) plotted against intercondylar length (mm) at Jebel Moya and Naqada (p<0.001 at both sites). As with total area, there is a correlation.

Comparisons of length plotted against *J* are very similar to the results of length plotted against TA, visible in Figures 7.8.7 and 7.8.10. *J* and TA are often correlated (Macintosh *et al.* 2014). An independent samples t-test confirmed that the difference between the sites is significant for all variables tested. Mean length at Jebel Moya is 425.76 mm and 371.52 mm at Naqada, a difference of 54.24; t=5.11, df=49, p<0.001. TA at Jebel Moya is 512.08 mm^2 and 400.77 mm^2 at Naqada, a difference of 111.31 mm^2; t=4.365, df=49, p<0.001. I_x/I_y at Jebel Moya is 1.628 and 2.439 at Naqada, a difference of -0.811; t=-7.251, df=49, p<0.001. I_{max}/I_{min} at Jebel Moya is 2.113 and 1.712 at Naqada; t=3.614, df=49, p=0.001. J at Jebel Moya is 48409.33 and 30562.47 at Naqada; t=3.909, df=49, $p<0.001$. The mean and standard deviation of these values at each site are shown in Table 7.8.11.

Site		TA (mm^2)	*Imax/Imin*	*Ix/Iy*	*J* (mm^4)
Jebel Moya	Mean	509.634	2.128	1.629	48136.361
	SD	93.183	0.417	0.329	18944.719
Naqada	Mean	400.774	1.712	2.439	30562.772
	SD	89.855	0.371	0.466	13472.62

Table 7.8.11 Values of mean CSG properties and standard deviations for the Jebel Moya and Naqada pilot sample. Jebel Moya is significantly higher for all CSG values except I_x/I_y, for which Naqada is higher.

In summary, Part A has shown that the tibias examined from Jebel Moya and Naqada are significantly different in length and all CSG values. Jebel Moya tibiae are higher in most values except I_x/I_y (e.g. the Jebel Moya tibiae have a mean TA of 108.86mm^2 higher than Naqada's). It is unclear why I_x/I_y is higher for the Naqada individuals; this may be explained by the lateral rotation of the tibial shaft, which in this sample was up to 30° lateral from anterior. This demonstrates that there is a clear difference between these two groups who, according to archaeological literature, practiced different subsistence strategies. The data also show a difference between males and females in the Jebel Moya assemblage. Thus the study will, moving forward, be unable to utilise individuals of ambiguous or unassigned sex. The study will attempt to clarify these subsistence-based and sex-based difference using cross-sectional geometry and morphometrics in order to discern whether there are distinct patterns in tibial shape based on sex and activity, and the possible links between the two such as sexual divisions of labour.

7.8.3 Part B: directional asymmetry

The pilot study was used to test for directional asymmetry between antimeres of the same individual to determine whether scanning both legs of an individual was worthwhile. Of the 88 tibiae originally examined from Jebel Moya, 42 are from the left side and 46 are from the right. In the majority of cases, the left and right tibiae do not come from the same individual: only 9 individuals had both tibiae with preservation levels suitable for study. As a result, more general comparisons are made here between left-sided tibiae and right-sided tibiae from both Jebel Moya and Naqada. While it is not indicative of true asymmetry for individuals, preservation prevents this from being measured.

For asymmetry, mean I_{max}/I_{min} and TA were compared for each site. The difference, while not statistically significant (p=0.234), does show a slightly higher mean ratio on the left side for each site, shown in Figure 7.8.12: at Jebel Moya, 2.18 left and 1.96 right; at Naqada, 1.81 left and 1.6 right. The TA range is shown as a boxplot in Figure 7.8.13, showing a slightly larger range on the right side, but not statistically significant (p=0.551). The difference between sides is negligible and is most likely due to preservation or sampling rather than actual directional asymmetry – additionally, mean length is higher on the left (397.22mm) than on the right (394.07mm).

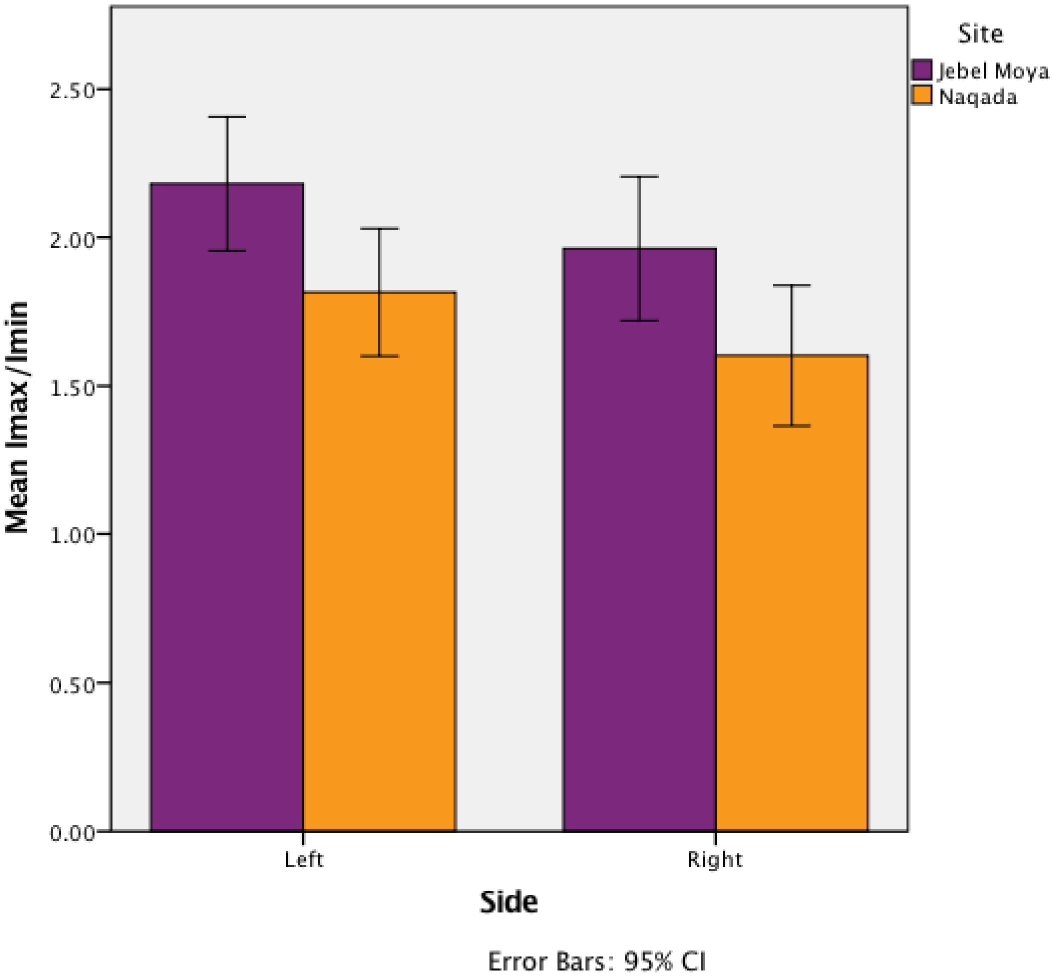


Figure 7.8.12 I_{max}/I_{min} compared for left and right tibiae by site. At Jebel Moya, the mean is 2.18 on the left and 1.96 on the right; at Naqada, 1.81 on the left and 1.6 on the right. Using a t-test, the difference is found to be not statistically significant (p=0.551).

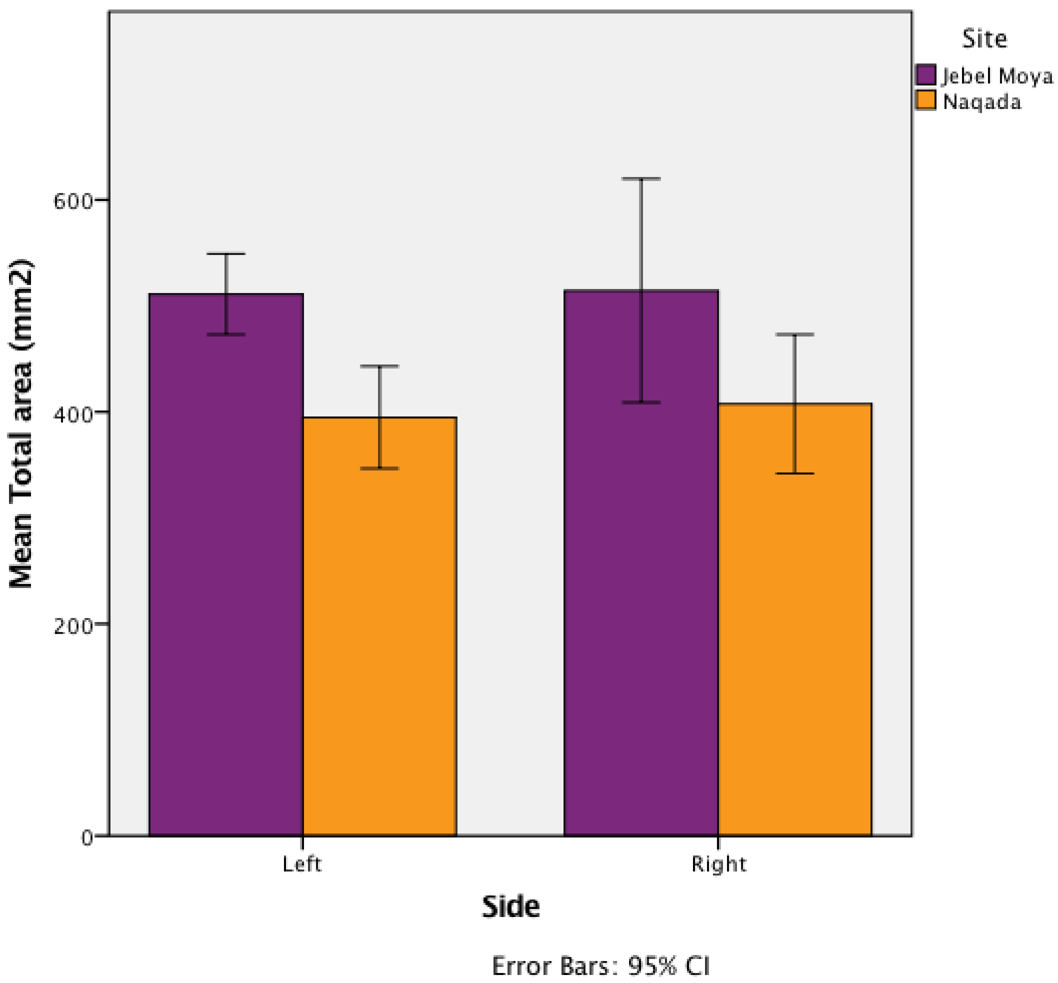


Figure 7.8.13 Mean total area compared for left and right tibiae by site. Left tibiae have a mean total area of 462.28mm^2 (SD=96.44) and right tibiae have a mean total area of 457.52mm^2 (SD=106.207). The difference between sides is not statistically significant at either site ($p=0.551$).

In summary, the number of individuals with both left and right legs preserved for comparison was low, so true directional asymmetry could not be tested. Comparisons of TA and second moments of area did not show a significant difference between all lefts and all rights. The difference between sides is not significant and is most likely the result of preservation or sampling rather than evidence of directional asymmetry. Of the individuals at Jebel Moya with two preserved tibiae, the left tibiae are selected for the main study, resulting in a reduction to n=70 and setting the standard that only one leg per individual would be used in the main study as preservation is not expected to be better in the other assemblages. However, the non-significant difference aligns with other studies that have noted very low levels of asymmetry in human legs (Auerbach and Ruff 2006; Macintosh *et al.* 2015).

7.8.4 Part B: Geometric morphometric and principal component analysis results

A sample of Jebel Moya tibiae (n=70) are used for geometric morphometric analysis as they are associated with skeletons. As the Naqada skeletons had no indication of sex or age (see Section 7.8.1), they could be analysed morphometrically but the results would not be comparable with those of Jebel Moya, clearly seen in Figures 7.8.1 and 7.8.2 above, where Naqada can only be represented as unassigned/ambiguous sex. The tibiae are divided by sex, including 48 males, 20 females, and 2 indeterminate. This is not reflective of the assemblage sex ratio, but rather the individuals with at least one preserved tibia.

The tibiae were each assigned to one of six shape categories using the descriptions discussed in section 7.6. Inter-observer error tests were conducted: three osteologically-trained individuals were shown the cross-section images and descriptions and then assigned them to categories. Cohen's kappa was run to determine if the observers were in agreement on shape category assignation. Between the initial observer (SH) and observer 1 (RW), k=0.946 (95% CI, 0.874-1.0), p<0.001; between the initial observer and observer 2 (MB), k=0.910 (95% CI, 0.829-0.982), p<0.001; between the initial observer and observer 3 (EF), k=0.893 (95% CI, 0.802-0.965), p<0.001. A k=1 indicates perfect agreement not by chance. All four individuals agreed on all assignations of the ovoid shape. The lowest agreement was on the triangular shape – it was assigned in 3 cases to be flat side, 3 cases to be half-moon, and 2 cases to be droplet. The percentage agreement between the initial observation and the additional observers is shown in Table 7.8.14. There was enough agreement to keep the categories stable. Note that percentage agreement is less valid than Cohen's kappa, but in this case both were used and indicate high levels of agreements between the observers.

Shape Cat (SH)	Observer 1 (RW)	Observer 2 (MB)	Observer 3 (EF)
Triangular	86%	80%	80%
Droplet	90%	100%	100%
Flat side	100%	94%	94%
Half-moon	100%	83%	100%
Diamond	100%	100%	87.50%
Ovoid	100%	100%	100%

Table 7.8.14 Agreement between the initially assigned shape categories and external observers, by percent

Both males and females are represented in each shape, but the droplet category has a higher percentage of females, shown in Figure 7.8.15. Additionally, those tibiae with the droplet cross-sectional form tend to be shorter, with the lowest mean length of all the shapes (396.23mm).

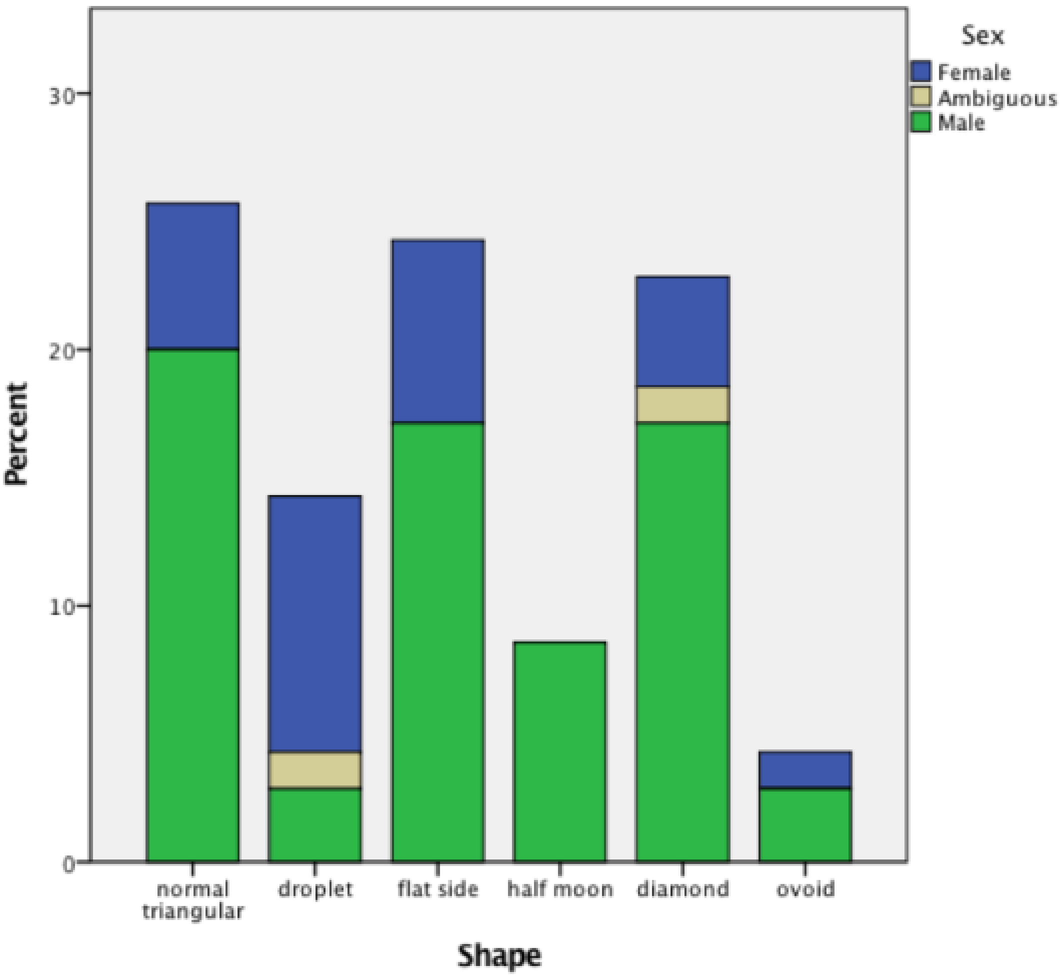


Figure 7.8.15 Shape categories by sex as a percentage of the Jebel Moya assemblage.

The shapes with the lowest percentage of females – half-moon and diamond – also tend to have the highest mean lengths (439.5mm and 422.125mm respectively, shown in Table 7.8.16).

Shape	Mean	N	SD
Triangular	415.556	18	26.395
Droplet	386.6	10	21.792
Flat side	409.882	17	26.445
Half-moon	439.5	6	18.78
Diamond	422.125	16	21.639
Ovoid	397.333	3	10.01

Table 7.8.16 Mean lengths for each tibial shape category within the Jebel Moya assemblage

After sorting into shape categories, the cross-sectional images were subjected to geometric morphometric analysis using Morphologika as described in section 7.5. Analysis included generalised Procrustes and principal component analysis. The number of principal components is equal to the number of variables entered, so there are six principal components for the tibial landmark data set. Firstly, although there is no clear grouping pattern, the male tibiae show a wider range across the y-axis while the females centre along the x-axis within a narrow range. This demonstrates that tibiae from Jebel Moya males have more variation in principal component 2. On the other hand, an almost equal distribution can be seen between male and female tibiae along principal component 1 (though the male tibiae continue further along the axis on both positive and negative sides). Visual examination within the tps (thin plate spline) space shows that principal component 1, accounting for 45.55% of variance, is the height of the posterior buttress and principal component 2, accounting for 22.11% of variance (cumulative total 66.66%) is the lateral side, varying between a sulcus and a flat side. While not aligning exactly with each shape category, these results disregard size and allow preliminary conclusions to be drawn: male tibiae at this site show more variation in the lateral sulcus while female tibiae show less. The average shape seen at the origin is between the droplet and diamond. Higher principal component 1 is more typically associated with the ‘diamond’ shape category, and higher principal component 2 is associated more commonly with the flat side shape. Unadjusted points are shown in Figure 7.8.17 below, where the x-axis is principal component 1 and the y-axis is principal component 2.

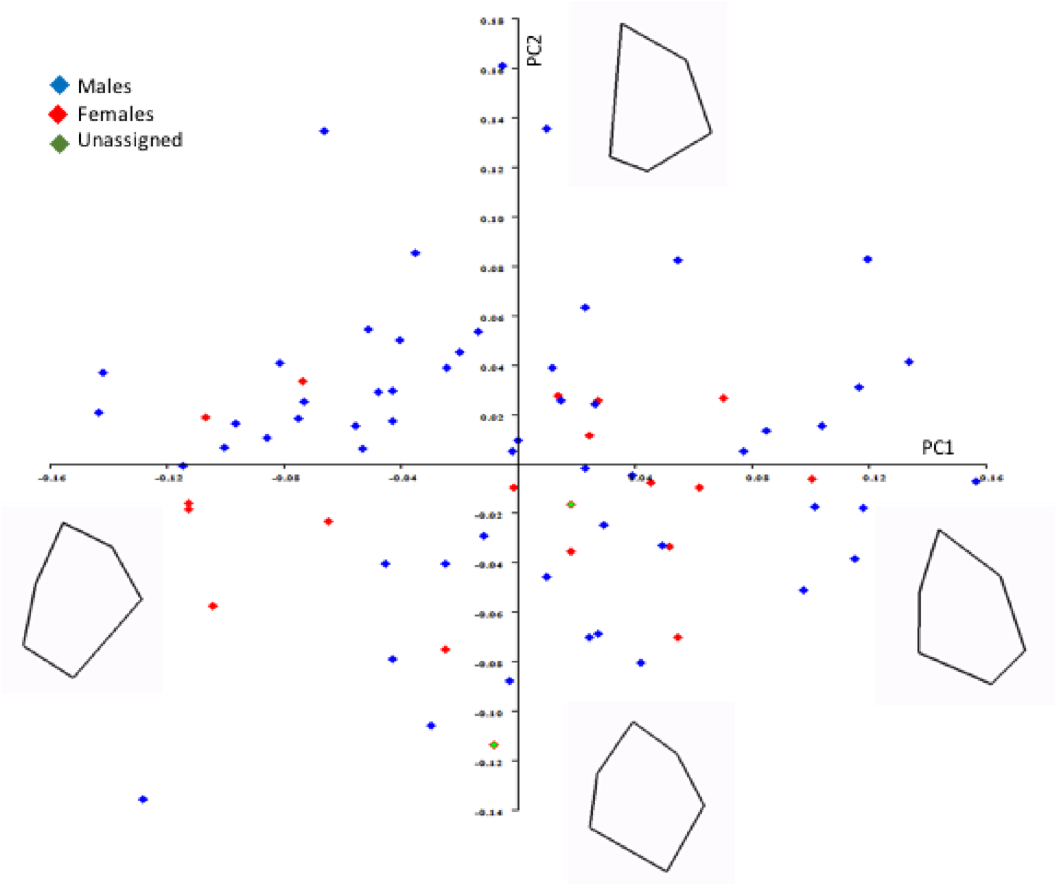


Figure 7.8.17 PC1 (x-axis) vs PC2 (y-axis) for the Jebel Moya sample; males in blue, females in red, indeterminate in green. Variance of PC1 is 45.55% and PC2 is 22.11%. Males show a greater range over PC2.

Further visual examination in the tps space determined that principal component 5 is also the lateral side, varying from a deep groove with a prominent interosseous crest to a slightly convex lateral surface. When compared with centroid size, a factor previously eliminated by the Procrustes, a trend can be seen, with female tibiae low on both principal component 5 (x-axis), accounting for 5.26% of variance, and centroid size (y-axis) and males high for both, shown in Figure 7.8.18. Female tibiae are both smaller than male tibiae and lack a lateral sulcus. However, as in principal component 1, the female tibiae do not extend all the way to a prominent interosseous crest but rather gather around the y-axis with a faintly convex lateral side.

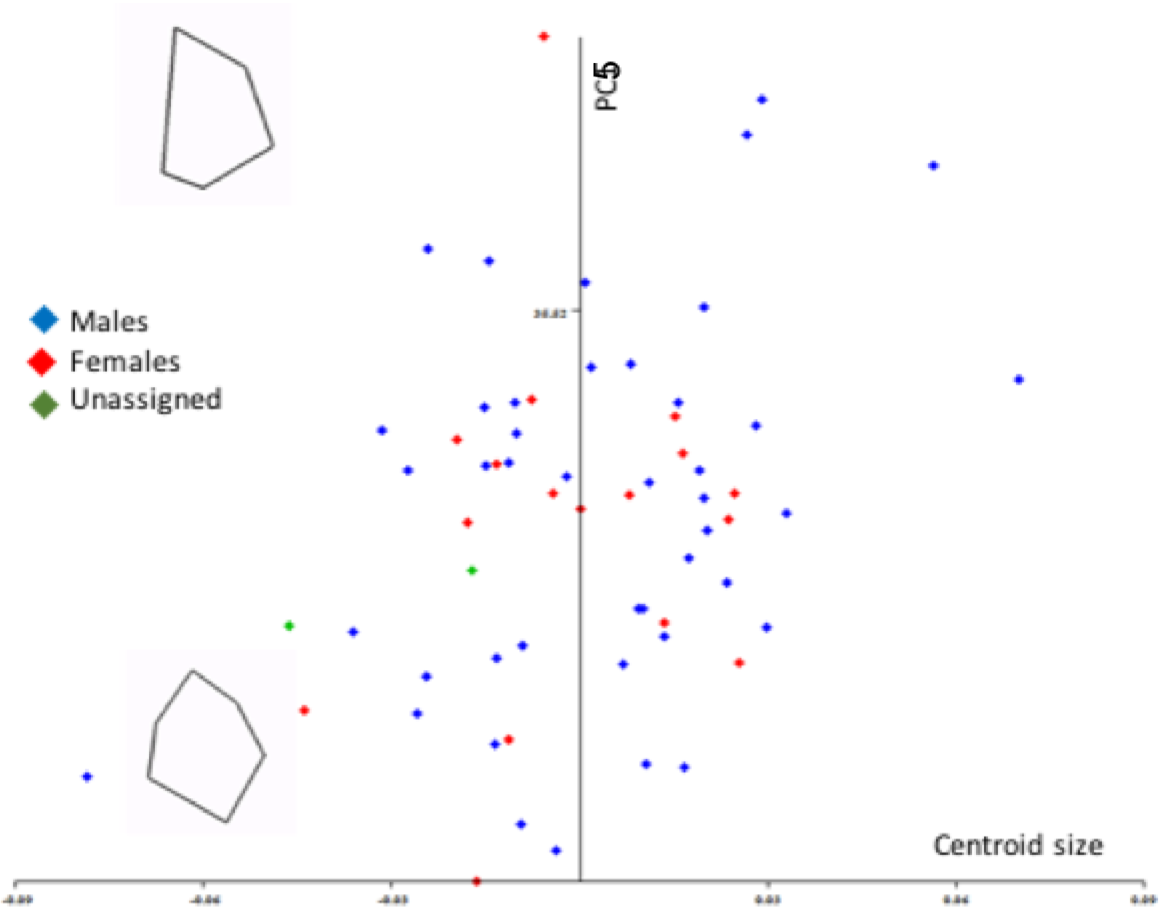


Figure 7.8.18 Centroid size (x-axis) plotted against PC5 (y-axis), with eigenvalue 5.26%. Males have a greater range along centroid size than females.

When principal components 1 and 2 are plotted against each other for shape (Figure 7.8.19), there is no clear trend as was seen with sex, above. At the time of the pilot study, only Morphologika was used. The main study investigates further using R, a more sophisticated program that does show trends based on shape.

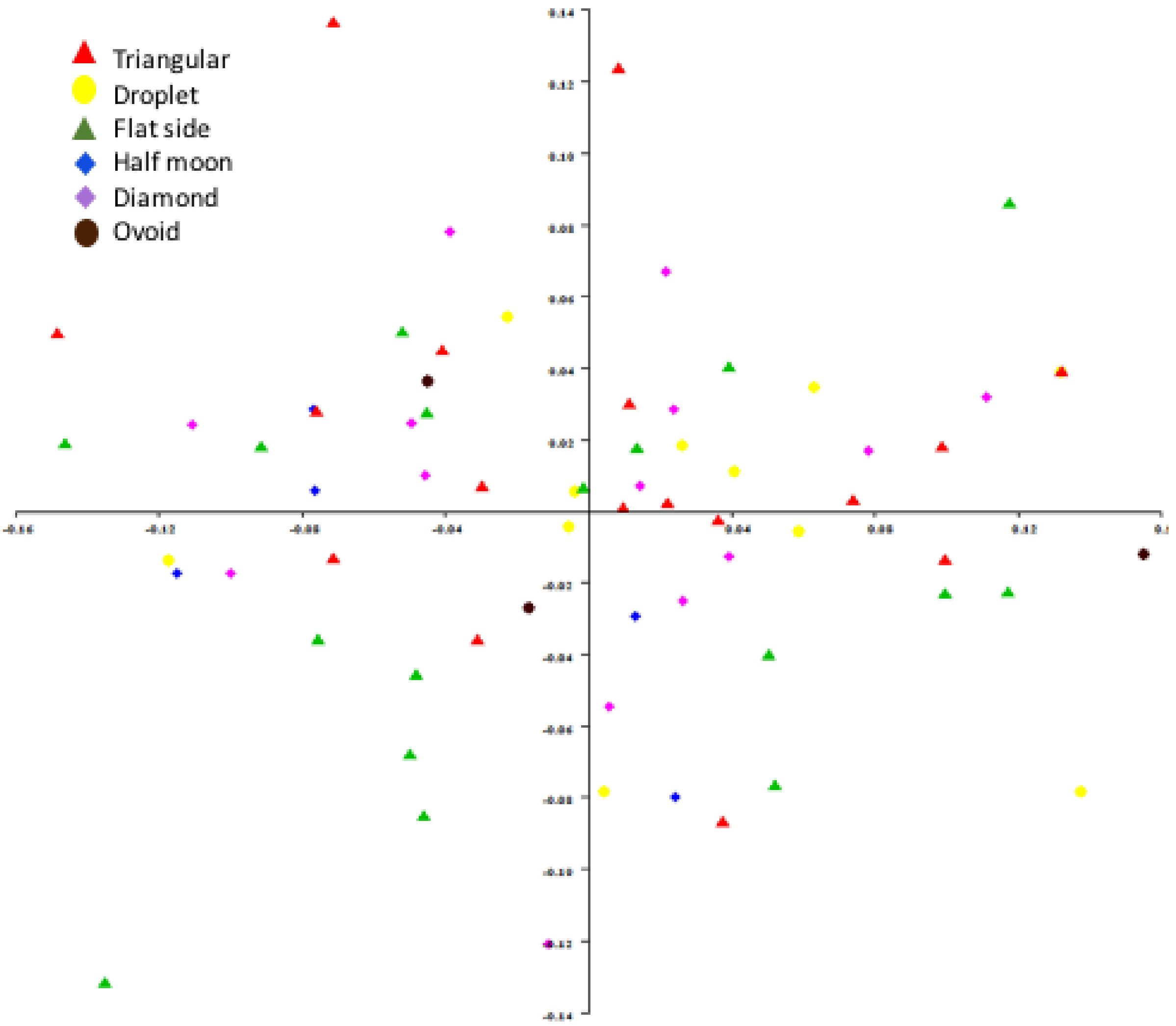


Figure 7.8.19 PC1 (x-axis, accounting for 46.036% of variance) plotted against PC2 (y-axis, accounting for 21.447% of variance) with shape categories. No trend is seen.

In summary, the shape categories are distinct and well-defined enough to be identified by outside observers. With principal component analysis, it was possible to distinguish differences between male and female tibiae at Jebel Moya, particularly with regard to their range on the principal component axes (i.e., male tibiae could be found at the extreme ends of each principal component while females clustered around the origin. The PCA results from this study demonstrated that the curvature of the lateral edge and the presence of a posterior buttress account for over 66% of the variance in shape when using six landmarks. These features can be related back to cross-sections and associated with sex categories.

PCA results for shape categories did not reveal any trends; this will be attempted again with more individuals and further subsampling by sex. As an initial finding, the pilot study determined that bilateral asymmetry is not significant enough in two ancient Nilotic groups to continue comparison (Figure 7.8.8). This was important to establish before moving forward with data collection, and enabled the study to focus on more individuals rather than inter-individual comparison. Tibial intercondylar length did not correlate to the CSG ratios (Figures 7.8.3 and 7.8.4), but it did correlate with the CSG properties indicating torsional and bending strength (Figures 7.8.2 and 7.8.5). This is similar to the correlation seen between length and midshaft diameters, so standardization by body size needed to be performed, otherwise larger individuals would continue to score higher for all CSG properties, and one aim of this study was to untangle that correlation.

7.8.5 Discussion and recommendations for full analysis

The pilot study, presented in Chapter 7.8, was conducted in two parts. Part A investigated the efficacy of using cross-sectional geometry to assess differences in subsistence strategy, a technique previously utilised by a number of researchers (Stock & Pfeiffer 2004; Nikita *et al.* 2011; Macintosh *et al.* 2014). As predicted, the results showed significant differences between the two sites, Jebel Moya and Naqada, for cross-sectional geometric properties and measurements.

First, length and midshaft diameters were compared. The tibiae from Jebel Moya (including a random selection of males and females) are longer than those from Naqada (sex undetermined) and are larger in anteroposterior and mediolateral midshaft diameters. The relation of length to diameter is expected, as bone expectedly grows larger in all dimensions (Ruff *et al.* 1993). Likewise, total area and length are correlated, explained again by bones growing larger in all dimensions; *J* (polar second moment of area) and length are also correlated.

Despite the small sample size, the results of Part A demonstrated that:

- differences are visible between groups of ancient individuals by cross-sectional geometry on the tibial midshaft, with Jebel Moya higher for all measurements as well as for values representing bending strength and torsional strength. Individuals from Jebel Moya are larger and stronger in these values than individuals at Naqada.
- there is no correlation between I_x/I_y and length, and there is no correlation between I_{max}/I_{min} and length.
- There is a correlation between TA and length, and there is a correlation between J and length.

This led to the use of standardised J and TA in the rest of the analysis, as they are linked to body size. Thus they cannot be accurately compared in this instance – since Jebel Moya individuals have longer tibiae than individuals at Naqada, TA and J will be artificially elevated, seen in Table 8.1.6. Conversely, neither second moment of area (I_x/I_y and I_{max}/I_{min}) is correlated with length: these appear to be extrinsic measures of rigidity unlinked to bone or body size.

Dissecting the second moments of area further is necessary. These compare the distribution of cortical bone around a centroid; a higher number means more bone is in the anteroposterior or maximum plane, and a lower number means more bone is in the mediolateral or minimum plane, respectively. As the score approaches 1, the bone shaft is more circular – or, since the tibia is never truly circular, a score closer to 1 can be described as more even distribution of bone around the centroid. For the ratio of second moment of area around the x- and y-axes (I_x/I_y), Naqada is higher than Jebel Moya. Despite their overall smaller size, the Naqada tibiae have more anteroposterior rigidity than the Jebel Moya tibiae. A higher I_x/I_y ratio is indicative of higher mobility; values tend to decrease as groups adopt agriculture (Larsen 2015: 355), which is the opposite of what is found here. This means that it is the Naqada agriculturalists (at least this small subset) who performed more mobile activity than the Jebel Moya pastoralists – an unexpected result. As mentioned above, the tibiae were grouped together and not discriminated by sex. This may have conflated some of the results, but also is important to remember for the remainder of the study as in many cases it is difficult to assign sex to ancient human remains. The small sample size may also have contributed to a skewing of results; the distribution of length for Jebel Moya in particular is multimodal. It is possible that the higher I_x/I_y ratio is due to the presence of extreme outliers in the Naqada group – an indicator of individuals performing differing activity from the majority - and an overall similarity between the individuals at Jebel Moya; the Jebel Moya I_x/I_y ratio is clustered around 1.9 while Naqada presents a wider range. Another explanation is the tibia's position in the scanner relative to the proximal and distal ends, which will be discussed below; others note that I_x/I_y is more sensitive to error in orientation during scanning (Stock & Pfeiffer 2001) unlike I_{max}/I_{min}, which is determined by intrinsic distribution of mass (Shaw & Stock 2009). For I_{max}/I_{min}, Jebel Moya tibiae are significantly higher, which would indicate the opposite of the above – that Jebel Moya is an assemblage representative of a more mobile population, which is the hypothesised result. Noting the difference in these values in the pilot study as well as in previous literature enables the remainder of the study to confidently assess differences between groups on the basis of CSG, and invokes the need to standardise TA and J to body size when possible.

Directional asymmetry was tested in Part B of the pilot study, using both Jebel Moya and Naqada. Unfortunately, not enough individuals had both a left and a right tibia to test true directional asymmetry (and Naqada tibiae were unmatched), so all lefts were compared to all rights using length, TA, and I_{max}/I_{min}. Part B demonstrated that:

- The difference between all lefts and all rights is not significant, but preservation prevents tests of asymmetry on individuals at Jebel Moya and most likely other sites in this area.
- inter-observer error showed agreement in assignation to the shape categories outlined in section 7.6.
- shape categories show a difference in overall percentage of shapes assigned to males and females

- shape categories show a difference in overall percentage of shapes assigned to males and females
- it is possible to examine differences between sex categories by principal component analysis of landmarks. Females show lower variation than males in principal component 1 as well as centroid size.
- It is not possible to distinguish shape categories by principal component analysis.

Although the mean values for the left side were slightly higher at both sites, the difference between left and right tibiae for these metrics was not significant, indicating that overall the individuals at Jebel Moya did not prefer one leg over another. Leg preference is seen in few archaeological examples, notably femoral diaphyseal torsion due to seating practices (Westcott *et al.* 2014) and greater anteroposterior bending strength in the femur and tibia for unclear reasons (Ruff & Hayes 1983; Wanner *et al.* 2007), although measurements indicating asymmetry in Wanner *et al.* (2007) were taken at the nutrient foramen rather than midshaft. Ruff & Hayes described the left-preference they observed in Pecos Pueblo females as the result of an obscure cause, but probably habitual-activity related such as "pushing off from the left leg during plowing or other agricultural tasks" (1983: 398) and that the right femoral neck is strengthened from these activities rather than the left. Since directional asymmetry and absolute asymmetry could not be tested using the pilot study sample but thus far indicated no significant difference, the decision was made to re-test asymmetry using an additional assemblage, and at this point to retain the null hypothesis that there would be no difference or that preservation would inhibit the further use of both antimeres.

Part B of the pilot study, also using the Jebel Moya assemblage, employed a geometric morphometric analysis. As described in Section 7.5, geometric morphometrics is the quantitative study of shapes. Using the same program that produces CSG results, cross-sectional midshaft images were obtained and divided into six groups based on those originally described by Hrdlička, discussed in Chapter 4.1.2. Inter-observer error tests showed that there was significant agreement between three observers. Images of the shapes and their descriptions can be found in Chapter 7.7: the descriptions are based on a combination of number of recognizable points (three or four) and sulcus on the lateral side. According to the biomechanical, medical, and exercise physiology literature, these shapes are arguably the result of a combination of biomechanical stresses and muscular activity, which will be discussed in Chapter 9. The breakdown of shape by sex at Jebel Moya led to an initial finding that was repeated at most of the other sites: females are found much more frequently in the droplet category than males, and less frequently in the other shape categories (Figure 8.1.10). When sex is removed as a factor, droplet-shaped tibiae tend to be shorter and have lower CSG values and half-moon and diamond-shaped tibiae tend to be longer, discussed further below. As shown above, there is a correlation between bone length and low values for TA and *J*, but it is unclear at this point to what extent bone length, sex, and shape are correlated. However, it should be noted that females do appear in other shape categories, although less frequently.

Part B of the pilot study also used a set of landmarks and semi-landmarks to obtain geometric morphometric data. These landmarks were normalised for size and rotation so that analysis only accounted for differences in shape. The first test performed was principal component analysis, which revealed that the first two principal components, accounting for 67.66% of variance, are the presence of a posterior buttress and the depth of the lateral sulcus. The posterior buttress is the defining feature of the four-sided tibiae, differentiating the diamond and half-moon shapes from the triangular and droplet. The lateral sulcus is seen on the diamond and half-moon as well; in other shapes, the lateral side is flat or, in some cases, slightly convex. Principal component analysis has in this case distinguished two of the features used to classify the shapes. Analysis of the graph (Figure 7.8.17) revealed a wider range of PC1 for males than for females, indicating that males display both extremes (large posterior buttress seen in diamond tibiae and no posterior buttress seen in triangular tibiae) while females do not experience these extremes – the droplet shape has a rounded posterior border but no buttress. Principal component analysis was not able to distinguish differences between shape categories (Figure 7.8.19). Despite this – and because of previous success in differentiating two factors in identifying shape differences – principal component analysis will continue to be used in the remainder of the study, as will the shape categories: later, they will be re-tested using the entire outline in addition to landmarks. The meaningfulness of the shapes from a biomechanical and biological standpoint will be discussed accordingly. Note that at this point the shape categories have been determined by visual examination based on early 20th-century anthropological assessments. Despite their replicability in inter-observer error testing, the shape categories might be entirely arbitrary; further outline analysis aims to clarify this.

The pilot study showed that the methods used by other researchers – using CSG to explore inter-site differences in tibial strength - are applicable to this study, but some need standardization for body size. Thus the Naqada tibiae were rejected from further analysis.

The remainder of the project expands on these results, testing the Jebel Moya assemblage discussed above in addition to three more sites. The results aim to show that patterns of tibial shape as represented by cross-sectional geometric properties and supported by 2D cross-sections vary by subsistence strategy and that it is possible to detect individual and communal patterns of activity. In order to explore the nature of these differences, more agricultural groups are tested and more advanced methods of examining 2D outline are utilised, exchanging Morphologika for Momocs.

This chapter has covered the methods that will be utilised in the next chapter: skeletal analysis with an aim to establish sex and age, physical examination and measurement, 3D laser scanning, finding values of cross-sectional geometric properties using AsciiSection, analyzing morphometric landmarks and outlines using Morphologika and Momocs, and conducting statistical analyses on the resulting data. It also presented the results of the pilot study with recommendations for further analysis. Note that the following chapter will continue to use abbreviations for cross-sectional geometric properties.

8 Results and Preliminary Observations

This chapter presents the results of the comprehensive analysis developed after the completion of the pilot study. The complete study differs from the pilot study as it uses all three Sudanese groups and the English medieval control group. The complete study results are presented in order of the type of analysis used (general frequency and means in section 8.1, cross-sectional geometry in section 8.2, and geometric morphometrics in section 8.3) with statistical analyses for each included in the relevant section. Shape analyses are included within each site analysis. Discussion of the results and their importance can be found in Chapter 10. Probabilities are given in full for significance tests, but the limit for acceptance or rejection of the null hypothesis is set at $p<0.05$. Note that when discussing cross-sectional geometric (CSG) values, the abbreviations assigned in Chapter 7 are used in accordance with the biomechanical literature.

8.1 Summary statistics, frequencies, and comparisons

This section displays the frequencies and means of all variables investigated found in the samples and sub-samples, including explanations of instances when data was excluded due to poor preservation or inadequate digitization. Counts of individuals in each group and subgroup are important to cover before data is presented so statistical significance can be assessed; categories which contain too few individuals are considered differently or dismissed. Likewise, means and standard deviations must be presented in order to address the variety inherent in the sub-samples examined. The entire data set used in the main study includes 254 tibiae; only one tibia was used per individual after the tests for asymmetry conducted as part of the pilot study were shown to be statistically insignificant, shown in Figure 8.1.7. Refer to Chapter 6.5 for total numbers of individuals in each site, age, and sex category.

Length and other direct tibial measurements are tested for normal distribution, and differences in measurements between sex categories and age categories when appropriate. The sections for each site display identical methods of data processing in order to compare them to each other: sex and age distribution, shape categories, tibial measurements, sexual dimorphism rates, and other strictly measurement-based descriptive variables. Individuals of ambiguous/unassigned sex are not included in calculations of sexual dimorphism.

8.1.1 Distribution

This section displays distributions of individuals, shapes, sites, and other categories that will be used in later analyses. Note that "all individuals" refers to all individuals from Jebel Moya, 3-J-18, Gabati, and Chichester, and that box plots show median values and quartiles rather than mean.

First, histograms of intercondylar length are examined. When examining overall length using a Shapiro-Wilk test, the distribution is normal (p=0.254), shown in Figure 8.1.1 and as a normal quantile-quantile (Q-Q) plot in Figure 8.1.2. The mean intercondylar length is 382.22 mm ± 32.398. Skewness is 0.199 and kurtosis is 0.066. When examining overall length by sex for males, females, and ambiguous/unassigned (Figure 8.1.3), the distribution is normal (respectively, p=0.236, p=0.971, and p=0.441).

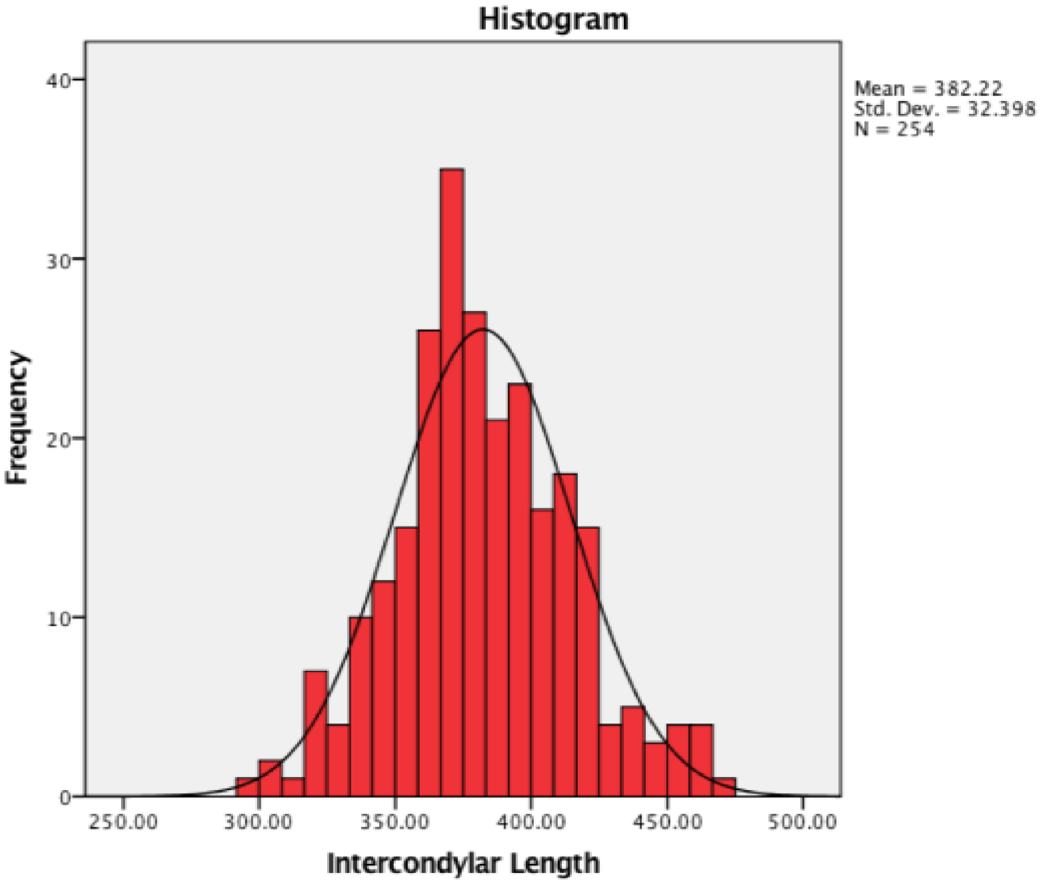


Figure 8.1.1 Histogram of tibial intercondylar length for all individuals in mm with normal curve (Shapiro-Wilk statistic=0.52, with 279 degrees of freedom, p=0.254). Note mean=382.22 mm and standard deviation=32.398.

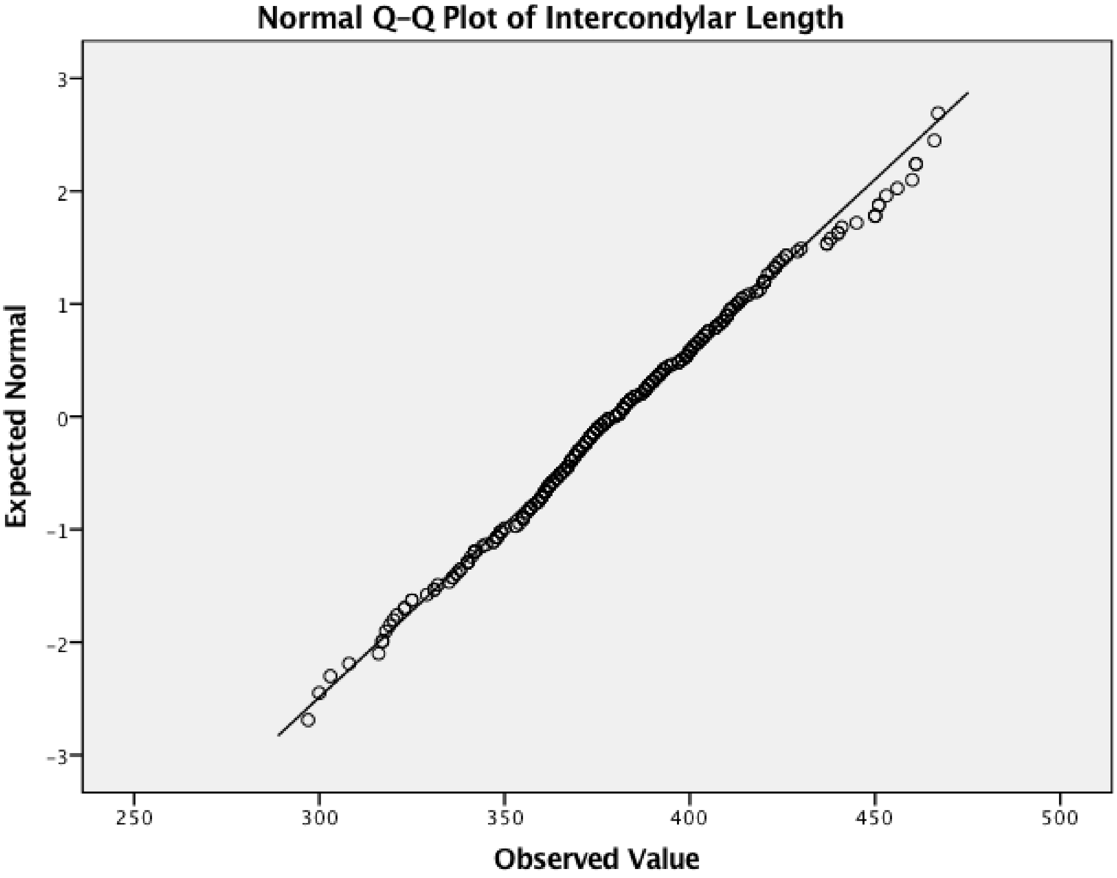


Figure 8.1.2 Normal Q-Q plot of tibial intercondylar length, showing outliers at the higher and lower ends but overall normal distribution (Shapiro-Wilk statistic=0.990, with 217 degrees of freedom, p=0.154).

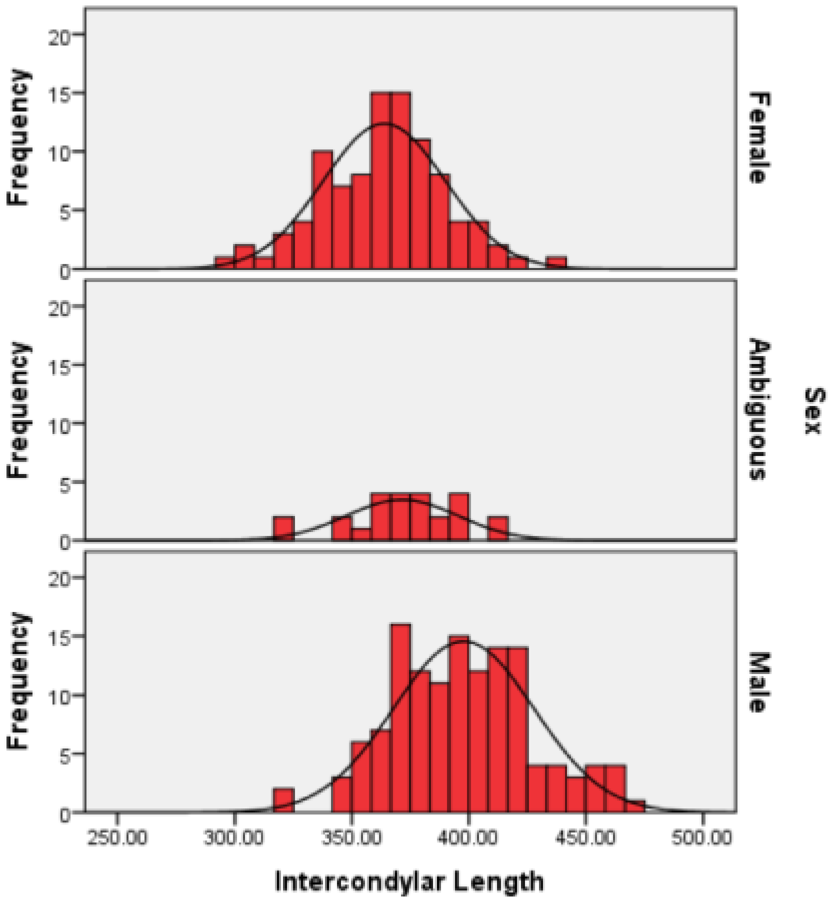


Figure 8.1.3 Histograms of tibial intercondylar length by sex with normal curves, showing normal distribution for females (Shapiro-Wilk statistic=0.060, with 97 degrees of freedom, p=0.971), ambiguous/unassigned (Shapiro-Wilk statistic=0.142, with 25 degrees of freedom, p=0.441), and males (Shapiro-Wilk statistic=0.985, with 108 degrees of freedom p=0.236).

Likewise, the distribution for femoral head diameter, anteroposterior diameter, mediolateral diameter, and TA and are shown to be normal using a Shapiro-Wilk test; the latter is shown in Figure 8.1.4 divided by sex (males p=0.77, females p=0.001, ambiguous/unassigned p=0.366). Note that distribution is not normal for male TA, possibly due to some missing values. An ANOVA was performed to determine whether the difference in length was statistically significant; it was significant (F(2,251)=42.772, p<0.005) between males and females. The difference between females and ambiguous/unassigned was not significant (p=0.447), but the difference between males and ambiguous/unassigned was significant (p<0.005). An ANOVA determined that the difference in anteroposterior diameter was statistically significant ((F(2,221)=64.081, p<0.001), and likewise for mediolateral diameter (F(2,221)=56.001, p<0.001).

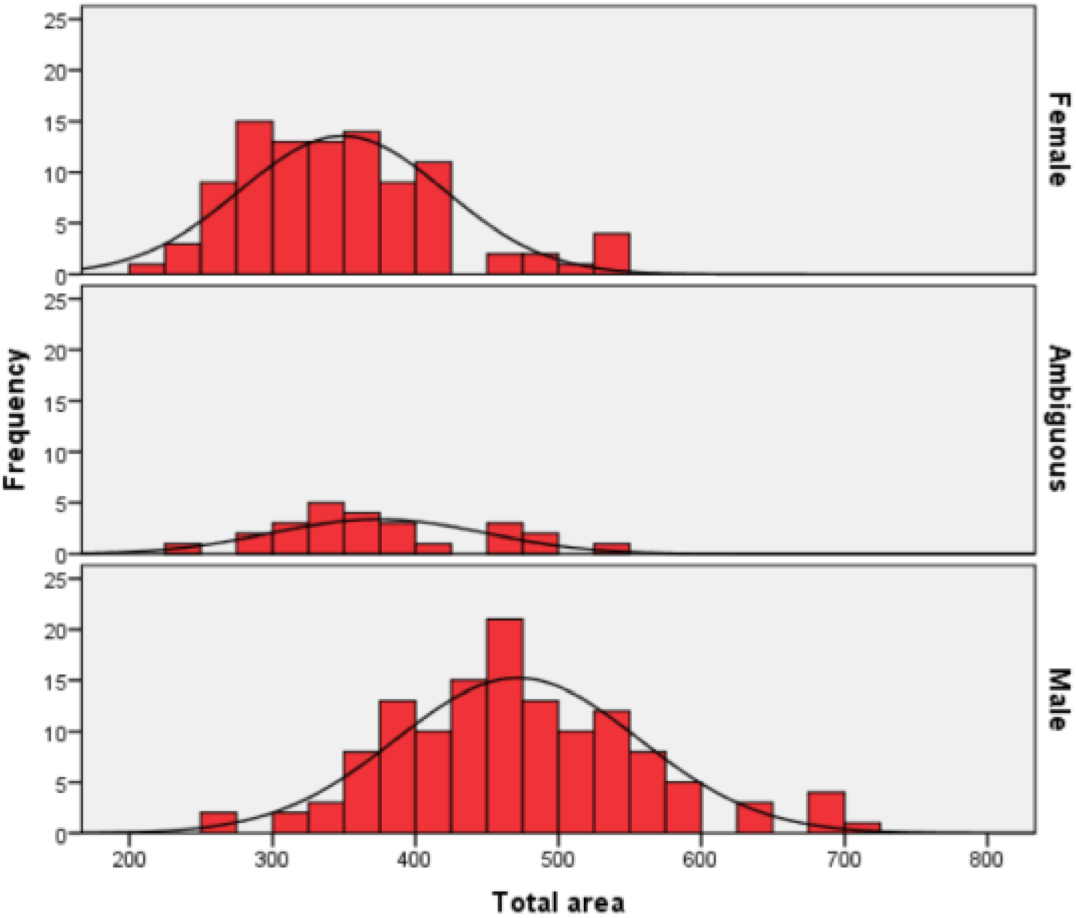


Figure 8.1.4 Histograms of total area by sex with normal curves, showing normal distribution for ambiguous/unassigned (Shapiro-Wilk statistic=0.961, with 23 degrees of freedom, p=0.481) and females (Shapiro-Wilk statistic=0.079, with 97 degrees of freedom, p=0.154) but not males (Shapiro-Wilk statistic=0.972, with 108 degrees of freedom, p=0.023)

To illustrate further normal distribution, results for TA by sex are also shown in a Q-Q plot in Figure 8.1.5, similarly showing normal distribution with outliers at the higher and lower ends of the plot.

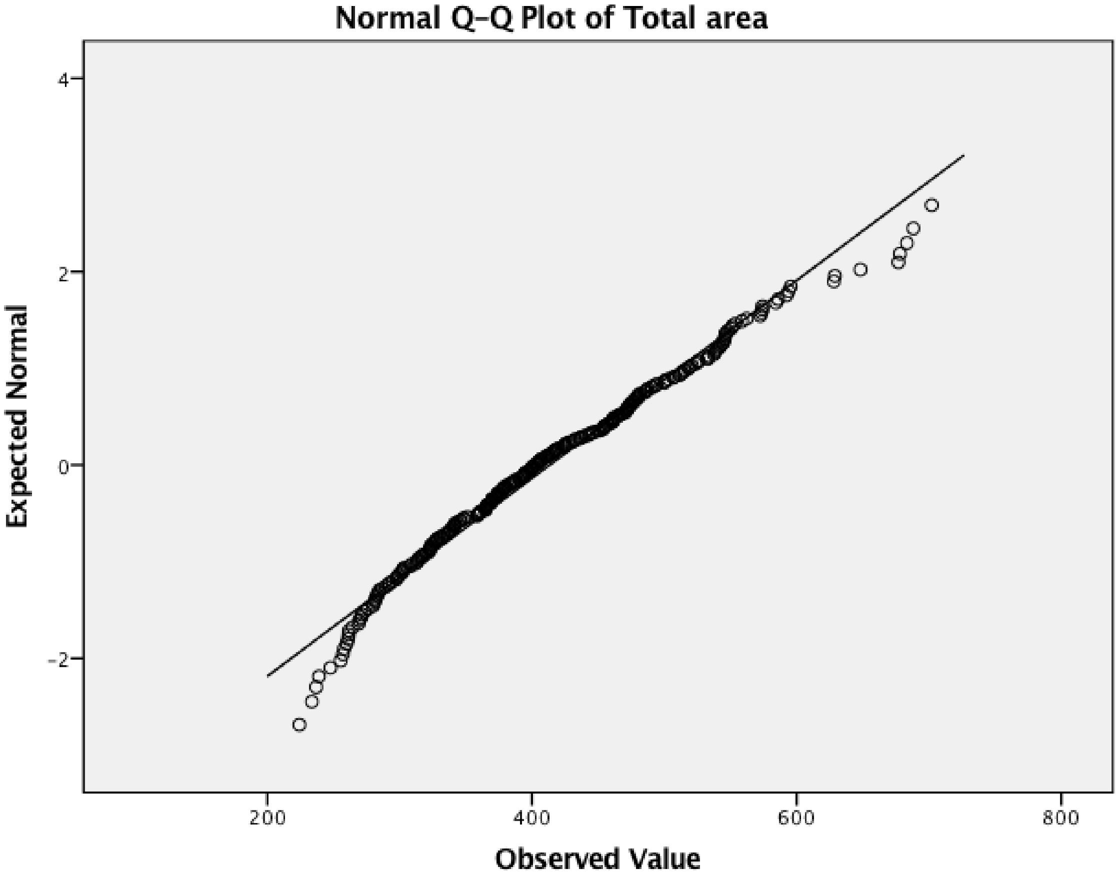


Figure 8.1.5 Normal Q-Q plot of total area for all individuals, showing outliers at the higher and lower ends (Shapiro-Wilk statistic=0.979 with 252 degrees of freedom, p=0.041).

Femoral head diameter was also tested: using a Shapiro-Wilk test, it is normally distributed (p=0.008). Femoral head diameter ranged in females from 33.5 mm to 45.3 mm (mean 39.27 ± 2.48) and in males from 38.7 mm to 53.5 mm (mean 45.18 ± 3.16). A histogram of log FHD is presented in Figure 8.1.6, a Q-Q plot showing normal distribution with outliers at each end in Figure 8.1.7, and a histogram of FHD by sex is presented in Figure 8.1.8 (female p=0.952, male p=0.388, ambiguous/unassigned p=0.253). While both show a normal distribution, the Q-Q plot reveals outliers at the higher and lower end.

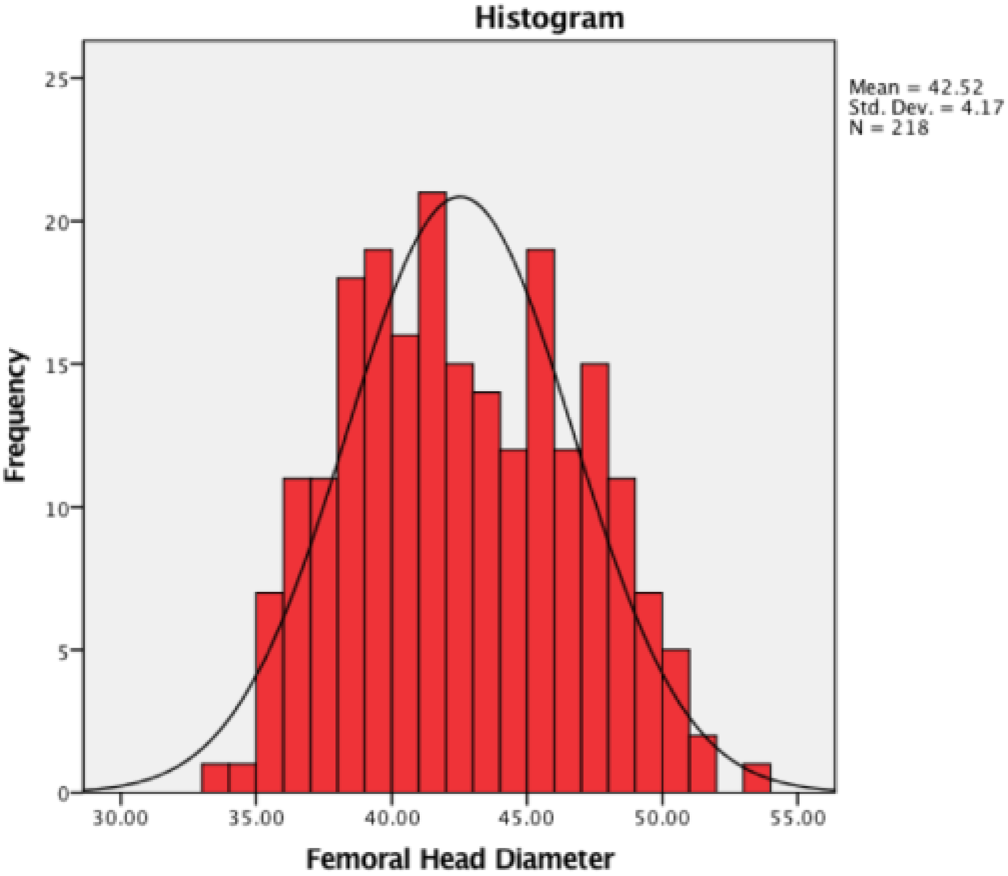


Figure 8.1.6 Histogram of femoral head diameter with normal curve (Shapiro-Wilk statistic=0.982 with 218 degrees of freedom, p=0.008).

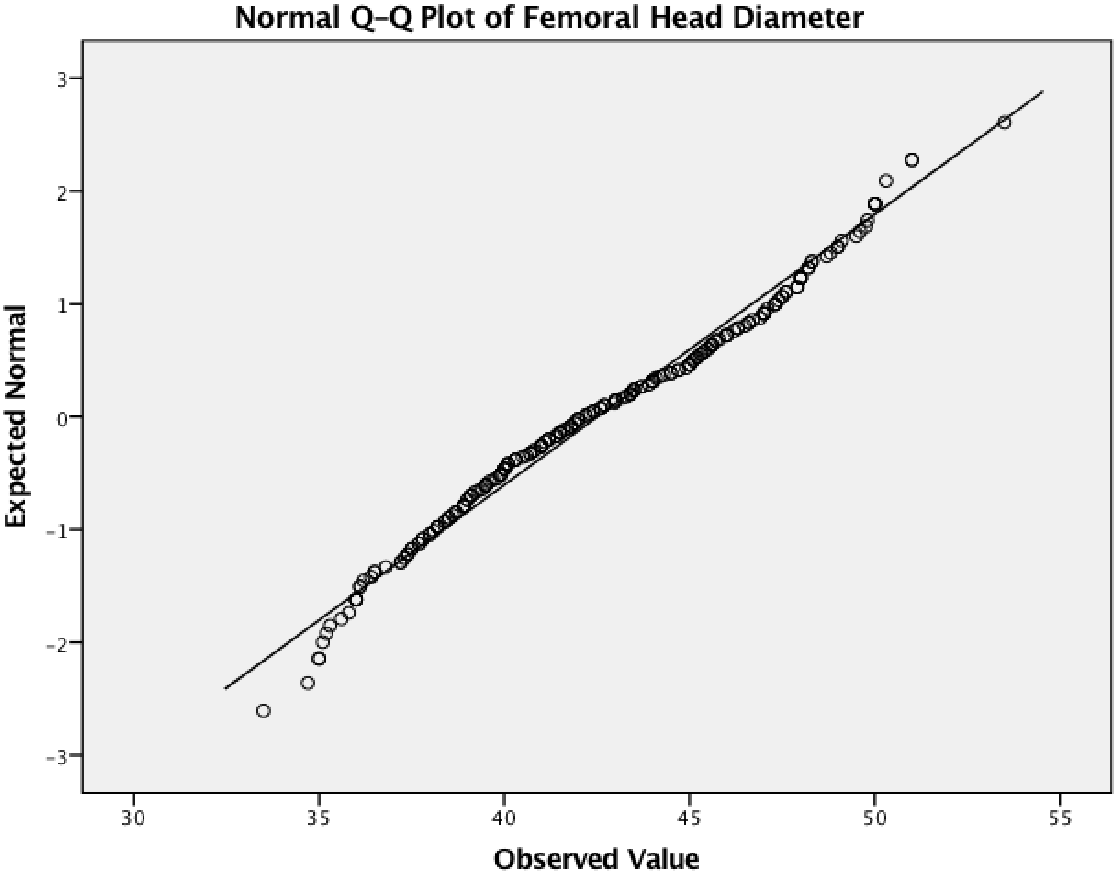


Figure 8.1.7 Normal Q-Q plot of femoral head diameter, showing outliers at the higher and lower ends (Shapiro-Wilk statistic=0.982 with 218 degrees of freedom p=0.008).

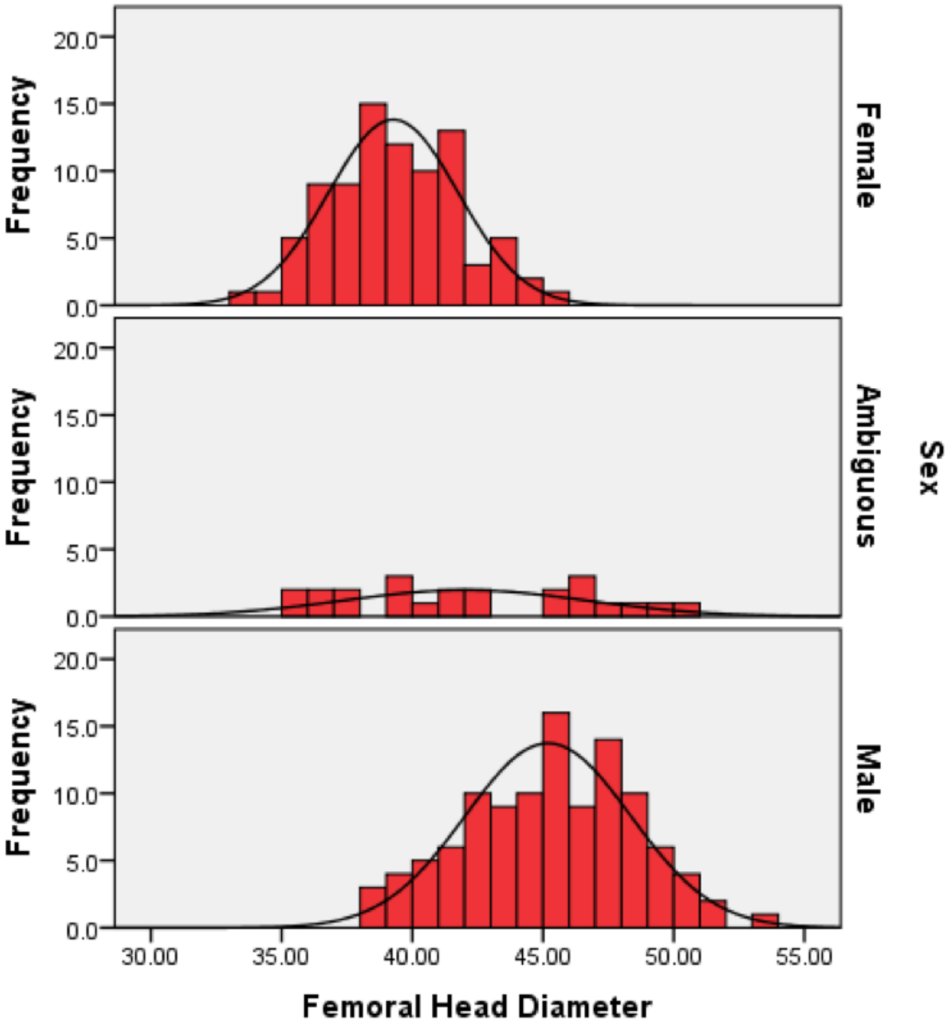


Figure 8.1.8 Histogram of femoral head diameter by sex with normal curves: female (Shapiro-Wilk statistic=0.994, with 86 degrees of freedom, p=0.952), male (Shapiro-Wilk statistic=0.987 with 108 degrees of freedom p=0.388), ambiguous/unassigned (Shapiro-Wilk statistic=0.947 with 23 degrees of freedom, p=0.253).

In summary, all measured variables tested are normally distributed when examined in aggregate and when divided by sex. This enables appropriate and accurate investigation using cross-sectional geometry and further statistical analyses.

8.1.2 Jebel Moya

This section discusses the particular frequencies and means of shape, intercondylar length, TA, and midshaft diameters at Jebel Moya.

Frequencies

Jebel Moya includes a total of 70 individuals: 20 females (28.6%), 48 males (68.6%), and 2 ambiguous/unassigned (2.9%). Individuals at Jebel Moya could not be aged due to poor preservation, so all are scored adult. This prevents the examination of distribution by age. The shape frequencies are shown in Table 8.1.9: The most common shape was triangular, although the balance was almost evenly divided between flat side and diamond.

Shape	N	% of Assembl
triangular	19	27.10%
droplet	10	14.30%
flat side	16	22.90%
half-moon	7	10.00%
diamond	15	21.40%
ovoid	3	4.30%
Total	70	100%

Table 8.1.9 Shape frequencies at Jebel Moya.

When examining the distribution of shape by sex (taking into account the uneven distribution of nearly three times as many males), it is clear that males are overrepresented in some categories (normal triangular n=15, half-moon n=11, diamond n=3) and underrepresented in droplet (n=2), shown in Figure 8.1.10. Shape and sex appear to not be correlated using a Pearson correlation (r=0.115, n=70, p=0.077).

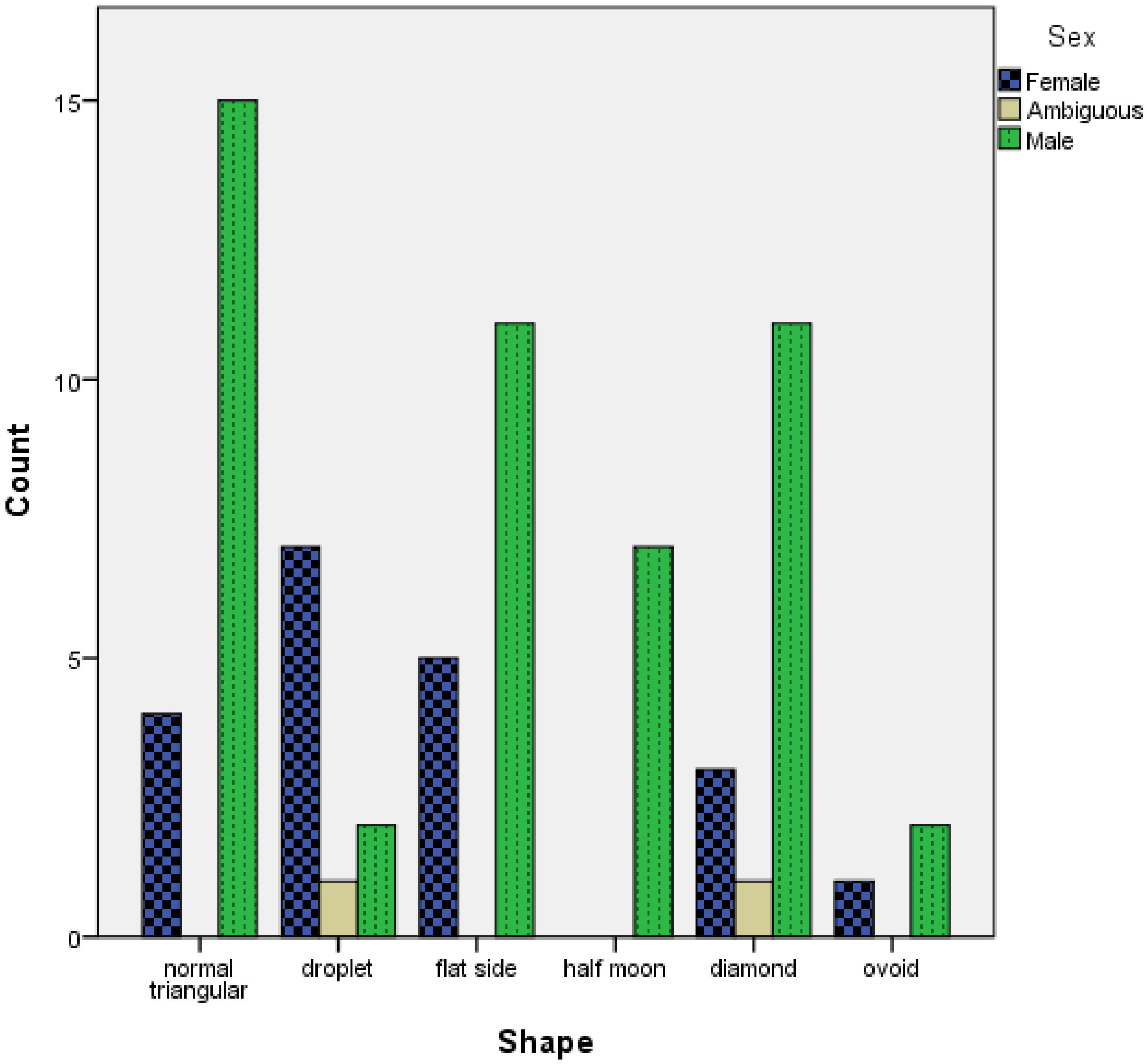


Figure 8.1.10 Bar chart showing shape frequencies at Jebel Moya divided by sex. The category most frequently assigned to males is triangular, and the category most frequently assigned to females is droplet.

Means

Tibial intercondylar lengths ranged from 360 mm to 467 mm, shown as a box plot in Figure 8.1.11. Female tibiae occupied a smaller range, and though male tibiae are generally longer, some are shorter than female tibiae: this could be due to errors in sex assignment, as these were not all performed by the author, instead relying on work done in the 1940s (Addison 1949). The mean length for female tibiae is 392.95 mm and for male tibiae 421.97 mm, a sexual dimorphism rate of 7.12%.

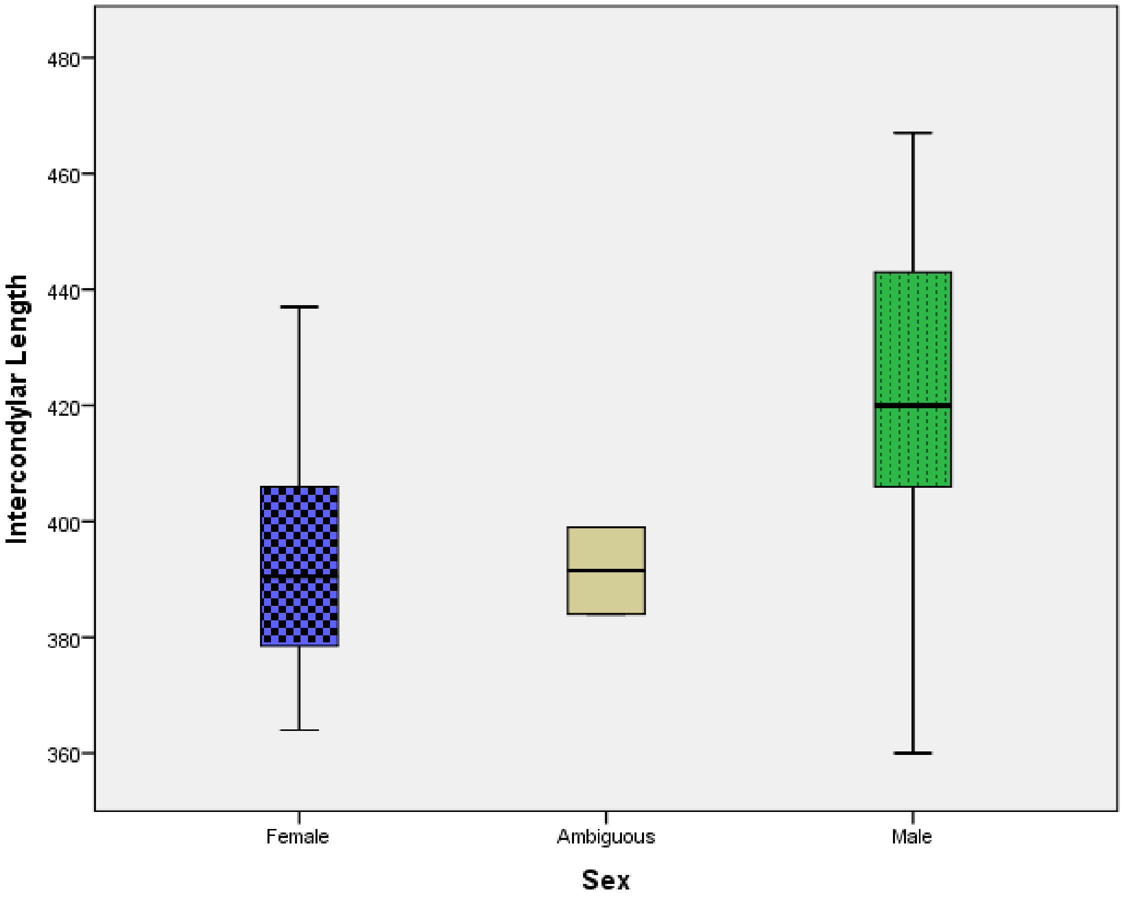


Figure 8.1.11 Boxplot showing tibial intercondylar length by sex at Jebel Moya, units in mm. Male tibiae have a greater range as well as a higher median.

TA, shown in Figure 8.1.12, was differently distributed: females tended to have a much smaller TA than males, with the female mean (446 mm^2) almost two standard deviations below the male mean (545 mm^2), resulting in a sexual dimorphism rate of 19.9%. However, there are four male outliers. Mean body mass for females, using equations from Auerbach and Ruff (2004) based on FHD, was 57.62 kg (±6.4) and 64.04 kg (±6.6) for males, resulting in a sexual dimorphism ratio of 10.55%. Individuals of ambiguous/unassigned sex are not included in these calculations.

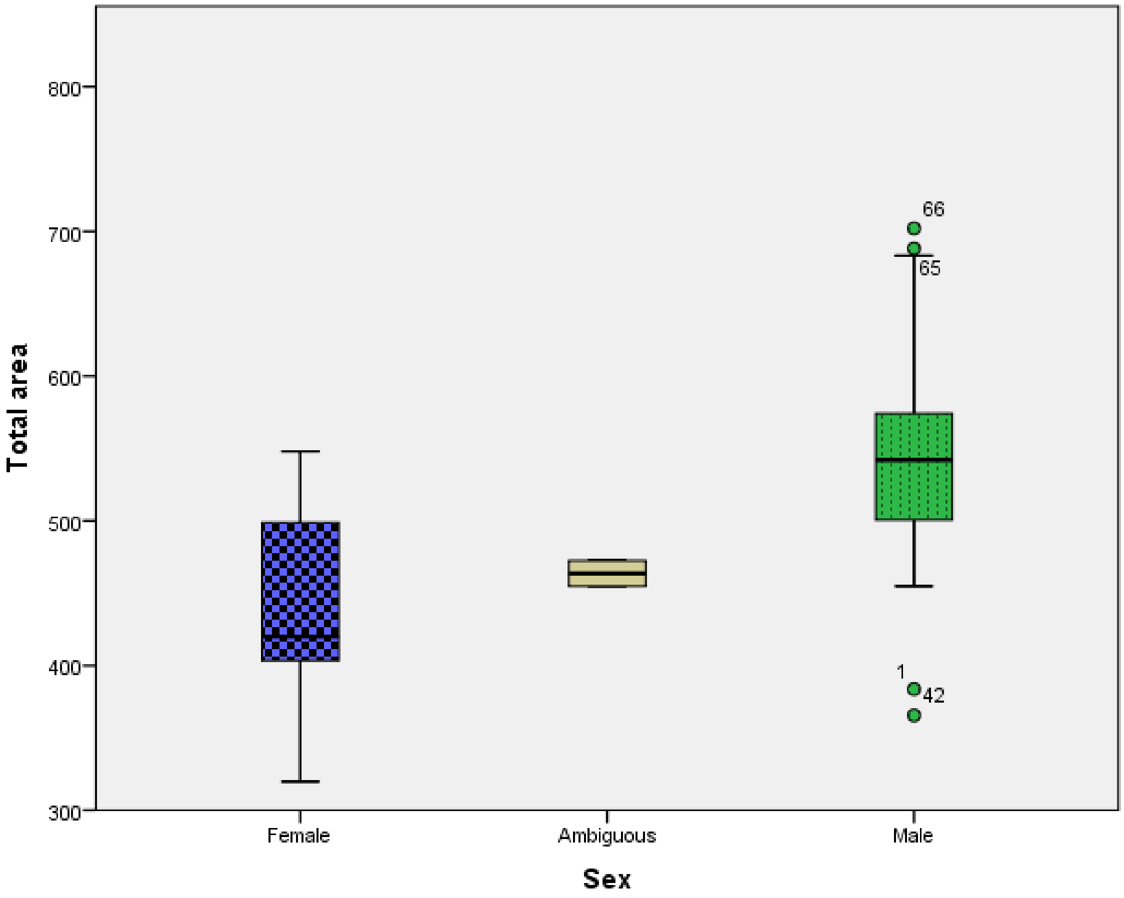


Figure 8.1.12 Boxplot showing total area by sex at Jebel Moya, units in mm^2.

When examining AP and ML diameters at midshaft, males are larger in both dimensions: while larger anteroposteriorly by an average of 2.42 mm and mediolaterally by 1.78 mm, they work out to a sexual dimorphism rate of 8.42% and 8.56%, respectively. These measurements and standard deviations are shown in Table 8.1.13.

	Females		Males	
	APdiam	MLdiam	APdiam	MLdiam
Mean	28.745	20.85	31.166	22.635
N	20	20	46	46
StdDev	3.764	1.771	3.505	2.353

Table 8.1.13 Female and male AP and ML measurements at Jebel Moya in mm.

Using a Student’s t-test, differences between males and females were shown to be significant for log length (t=4.666 with 68 degrees of freedom, p<0.001), log standardised

TA (t=-2.43 with 38 degrees of freedom, p=0.02), log standardised J (t=-2.096 with 38 degrees of freedom, p<0.001), log FHD (t=-5.397 with 39 degrees of freedom, p<0.001), log AP diameter (t=-4.491 with 64 degrees of freedom, p<0.001), and log ML diameter (t=-4.727 with 63 degrees of freedom, p<0.001). The sexual dimorphism rates for the log functions are as follows: length, 1.17%; standardised TA, 3.88%; FHD, 3.23%; AP diameter, 3.58%; ML diameter, 3.96%, and standardised *J*, 4.64%.

In summary*,* these data shows the following:

- Triangular is the most frequently-observed shape category for males, and droplet for females
- Tibial length ranged from 360 mm to 467 mm (females 365-448 mm, males 360-467 mm)
- Total ranged from 415-680 mm^2 (females 315-540 mm, males 450-680 mm excluding outliers)
- Males larger on average than females in diametric measurements by <1 SD and overall dimorphism 3.14%

8.1.3 3-J-18

This section covers the particular frequencies and means of shape, intercondylar length, TA, and midshaft diameters at 3-J-18.

Frequencies

3-J-18, the Mis Island site, includes a total of 87 individuals: 38 females (43.7%), 40 males (46%), and 9 ambiguous/unassigned (10.3%). Only 4 individuals are assigned to the adult age stage (4.6%). 42 individuals are 20-35 (48.3%), 35 are 35-50 (40.2%), and 5 are 50+ (5.7%). The shape frequencies are shown in Table 8.1.14, excluding 1 individual due to data error. The most frequently observed shape is flat side (26 individuals), closely followed by triangular.

Shape	N	% of Sample
triangular	24	27.90%
droplet	15	17.40%
flat side	26	30.20%
half-moon	9	10.50%
diamond	1	1.20%
ovoid	11	12.80%
Total	86	100%

Table 8.1.14 Shape frequencies at 3-J-18.

Similar to Jebel Moya, 3-J-18 females are overrepresented in the droplet category (n=12) and underrepresented in ovoid (n=2), half-moon (n=2), and absent from diamond, shown in Figure 8.1.15. Males and females are evenly distributed in the triangular shape category (male n=10, female n=12). It should be noted that shape category does not have a normal distribution. For this site, shape and sex are correlated using a Pearson correlation (r=0.287, n=86, p=0.007).

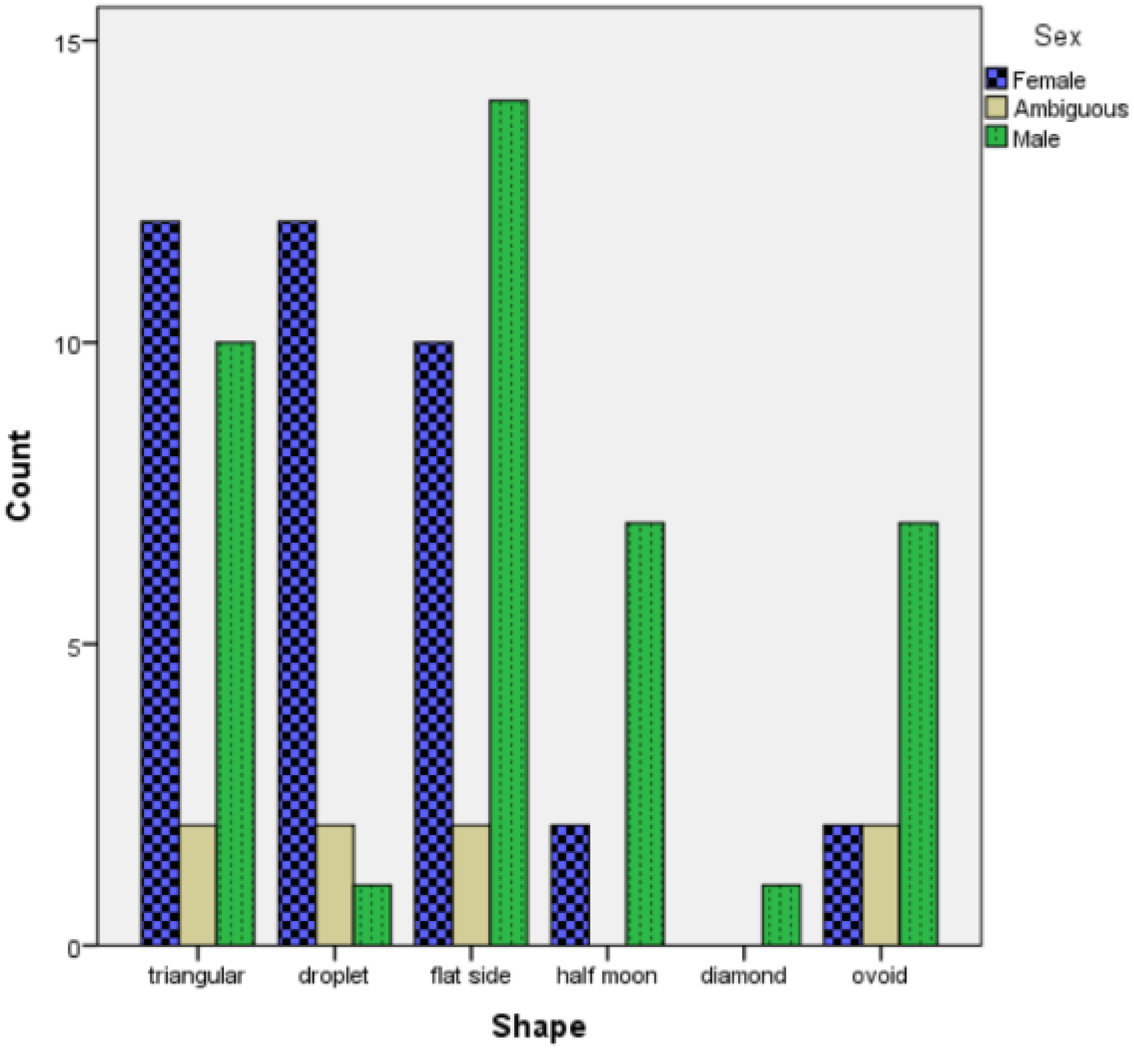


Figure 8.1.15 Bar chart showing shape frequencies at 3-J-18 divided by sex.

Age was compared to shape, but the correlation was not significant as most individuals are in the 20-35 (young adult) category.

Means

Tibial intercondylar lengths range from 317 mm to 430 mm – overall shorter than Jebel Moya. There is also a more clear-cut difference between males and females, in that males do not exceed females in both directions (with the exception of one outlier). Additionally, the male and female means are closer together (365.02 mm vs 390.8 mm), yielding a sexual dimorphism rate of 6.82%. The mean body mass estimate for females is 53.99 kg (±4.71) and for males 59.79 kg (±7.04), yielding a sexual dimorphism rate of 10.2%. This is shown in Figures 8.1.16 and 8.1.17. With the exception of one outlier, lower two quartile male TA values are equivalent to the top two quartiles of female TA values.

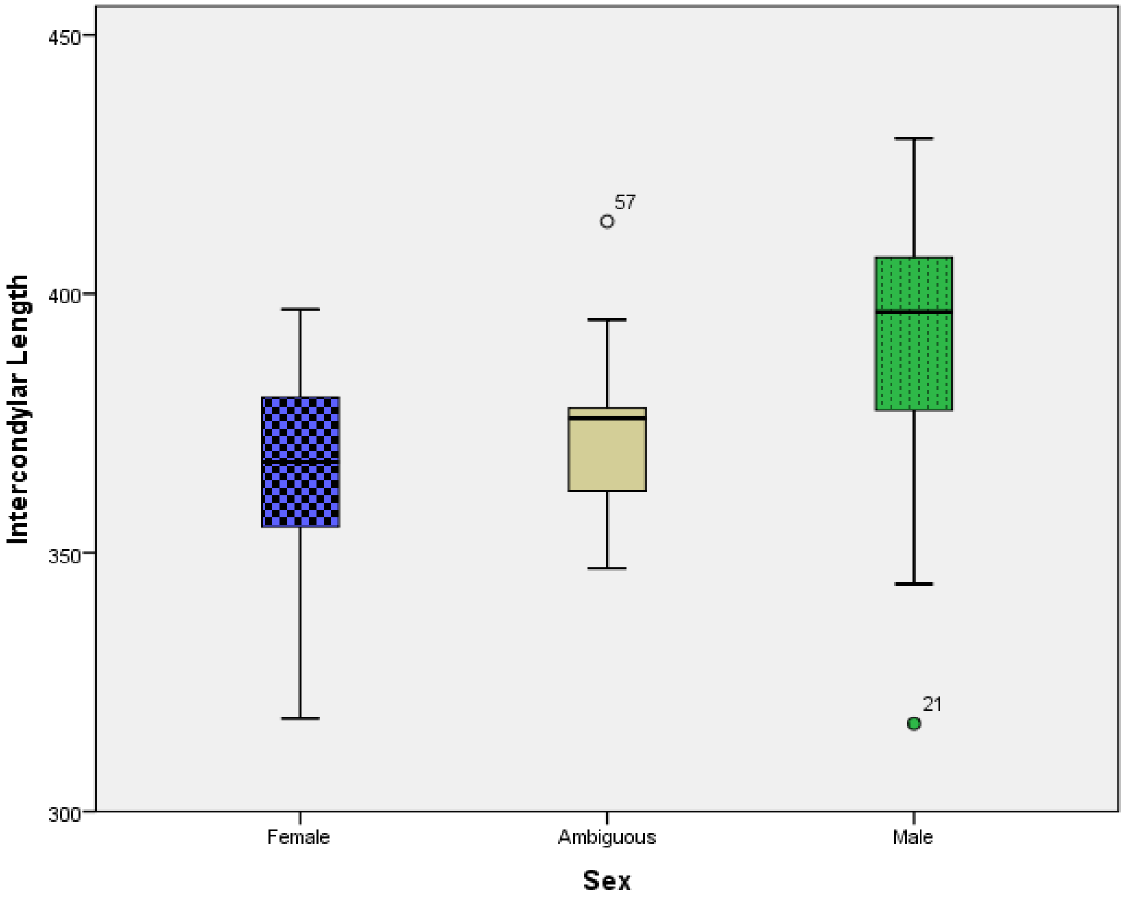


Figure 8.1.16 Boxplot showing tibial intercondylar length by sex at Jebel Moya, units in mm.

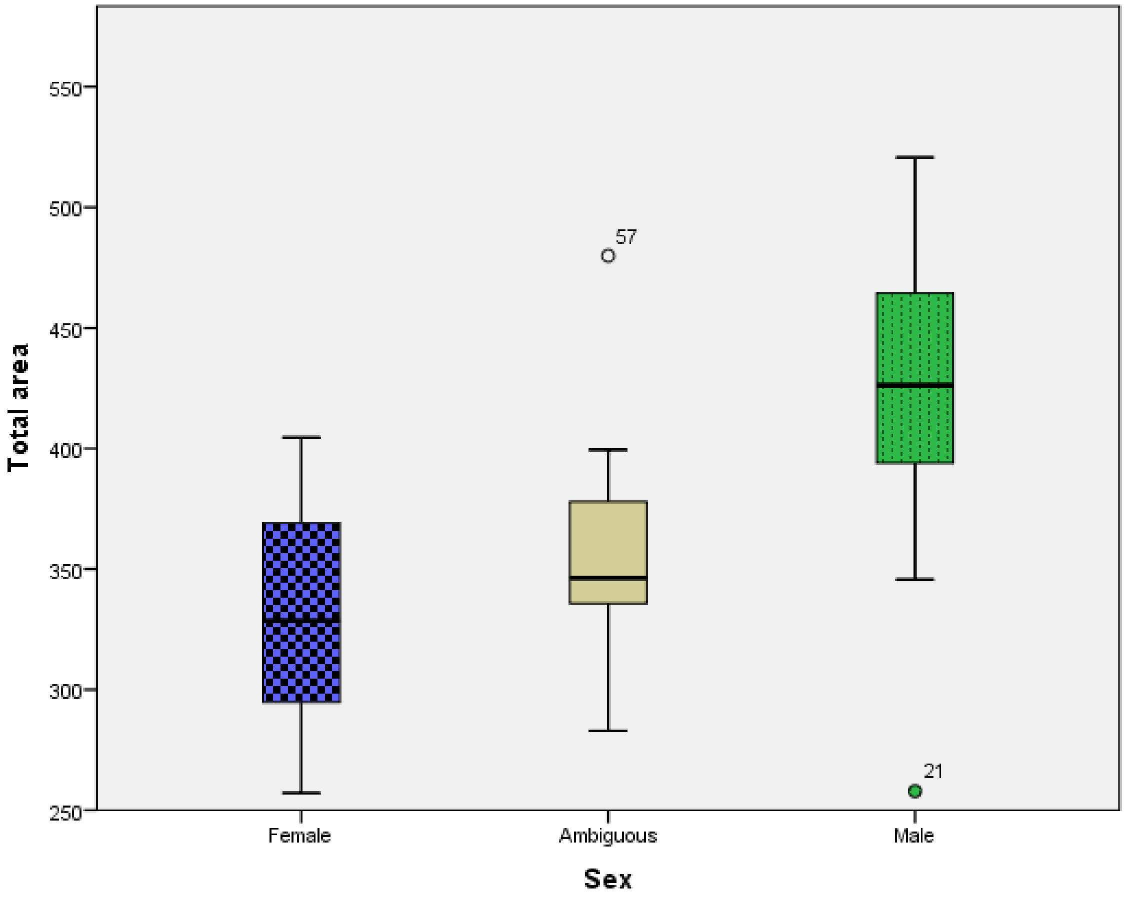


Figure 8.1.17 Boxplot showing total area by sex at Jebel Moya, units in mm^2.

When examining AP and ML diameters at midshaft, female tibiae are smaller in both dimensions by 1.16% and 1.12%, respectively. Note that the difference between males and females at 3-J-18 is approximately the same as the difference between each sex here and at Jebel Moya (scaled up), shown in Table 8.1.18.

	Females		Males	
	APdiam	MLdiam	APdiam	MLdiam
Mean	24.421	18.345	28.36	20.58
N	37	37	35	35
StdDev	1.754	1.426	2.066	1.998

Table 8.1.18 Female and male AP and ML measurements at 3-J-18 in mm.

Using a Student's t-test, differences between males and females were shown to be significant for log length (t=-4.908 with 76 degrees of freedom, p<0.001), log standardised

TA (t=-5.87 with 74 degrees of freedom, $p<0.001$), log standardised *J* (t=-6.71 with 74 degrees of freedom, $p<0.001$), log FHD (t=-8.75 with 74 degrees of freedom, $p<0.001$), log AP diameter (t=-8.532 with 70 degrees of freedom, $p<0.001$), and log ML diameter (t=-5.427 with 70 degrees of freedom, $p<0.001$). The sexual dimorphism rates for the log functions are as follows: length, 1.18%; standardised TA, 8.28%; FHD, 3.29%; AP diameter, 4.7%; ML diameter, 3.78%; and standardised J, 9.23%.

In summary, these data show the following:

- The most frequent shape is flat side for males, and triangular and droplet for females
- Length ranged from 317 mm to 430 mm (317-395 mm for females, 345-430 mm for males)
- TA ranged from 255-520 mm^2 (255-405 mm^2 for females, 350-520 mm^2 for males)
- Females smaller than males in both diameters by ~2 SDs, with an average dimorphism rate of 5.07%

8.1.4 Gabati

This section discusses the particular frequencies and means of shape, total intercondylar length, TA, and midshaft diameters at Gabati. It also discusses the results of the tests for asymmetry referred to in the pilot study (see section 8.1.3).

Asymmetry

Tests for directional and absolute asymmetry were conducted using the 25 Gabati individuals (45.45% of the total) who had both complete tibiae for the values length and TA. Directional asymmetry is the measure of right or left dominance: for length, the value was positive (0.08%), indicating a very slight right-side dominance (that is, the right tibia is 0.08% longer than the left), but for TA, the value was negative (-1.25%), indicating a slightly larger TA at midshaft on the left side. Absolute asymmetry is the amount of random asymmetry between sides: for length, the amount of absolute asymmetry is low at 0.44%, but for TA, the amount is 7.56%. Between individuals, the values of directional and absolute asymmetry for each measurement are identical if positivity/negativity is disregarded (e.g. one individual's absolute asymmetry is 0.053% and directional asymmetry is -0.053%), so the discrepancy between the means is most likely due to that. Differences in length averaged 1.73 mm and differences in TA averaged 21.52 mm^2. It is unclear why the amount of absolute asymmetry is higher than the other values, but could be due to TA being measured in mm^2 and length in mm, or to the small sample size, once again due to preservation. The difference between the amount of asymmetry observed in TA and length could be due to increased stress on a shorter leg, or could be random fluctuation. Table 8.1.19 displays the results of the tests for asymmetry.

	AA Length	DA Length	AA TA	DA TA
N	25	25	25	25
Mean	0.44%	0.08%	7.56%	-1.28%
St Dev	0.391	0.592	9.699	12.325

Table 8.1.19 Results of tests for absolute asymmetry (AA) and directional asymmetry (DA) for length and TA. The number of individuals, mean, and standard deviation are given.

Despite the small sample size, a Wilcoxon signed-rank test was run as it does not require normal distribution. The results showed that left and right lengths are not significantly different (Z=-0.811, p=0.417) and that left and right TA values are not significantly different (Z=-0.143, p=0.886).

Frequencies

Gabati includes a total of 55 individuals: 24 females (43.6%), 26 males (47.3%), and 5 ambiguous/unassigned (9.1%). 9 individuals are assigned to the adult age stage (16.4%), 29 are 20-35 (52.7%), 16 are 35-50 (29.1%), and 1 is 50+ (1.8%). Gabati can be divided into three time periods, Meroitic, Post-Meroitic, and Medieval, as discussed in Chapter 6; 20 individuals (36.4%) are from the Meroitic period, 20 from Post-Meroitic, 8 (14.5%) from Medieval, and for 7 (12.7%) the period is unknown. As there are only 55 individuals, this reduces the sample for each period – further divided by sex – making the statistical analyses used in the rest of this chapter unreliable. However, the numbers for each will be presented alongside total data from Gabati. Table 8.1.20 displays the number of individuals of each sex by time period.

	Female	Un/Am	Male	Total
Meroitic	6	3	11	20
Post-Meroitic	12	0	8	20
Medieval	4	0	4	8
Unknown	2	2	3	7
Total	24	5	26	55

Table 8.1.20 Sex distribution by time period at Gabati. Most females are from the Post-Meroitic period, while most males are from the Meroitic period.

The shape frequencies are shown in Table 8.1.21, excluding 3 individuals due to data error. In this group, the droplet category was the most frequent, with 14 individuals (25.5%), then triangular and flat side, shown in Figure 8.1.22. As there are only 55 individuals, it should be noted that statistical tests should be interpreted with caution: actual numbers will be discussed in addition to p-values.

Shape	N	% of Sample
triangular	10	19.20%
droplet	14	26.90%
flat side	10	19.20%
half-moon	6	11.50%
diamond	8	15.40%
ovoid	4	7.70%
Total	52	100%

Table 8.1.21 Shape frequencies at Gabati.

Once again, females are overrepresented in the droplet shape category (female n=13, ambiguous/unassigned n=1), while males outnumber females in all other categories except half-moon. The correlation between shape and sex is significant here using a Pearson correlation (r=0.281, n=52, p=0.044). This is shown in Figure 8.1.22. Shape distribution was examined by period: the most frequently observed shape in Meroitic is triangular (n=5), and in Post-Meroitic and Medieval it is droplet (n=7 and n=4, respectively). This is most likely linked to the distribution of sex from each period, as there are more males assigned to the Meroitic period and females to the Post-Meroitic period.

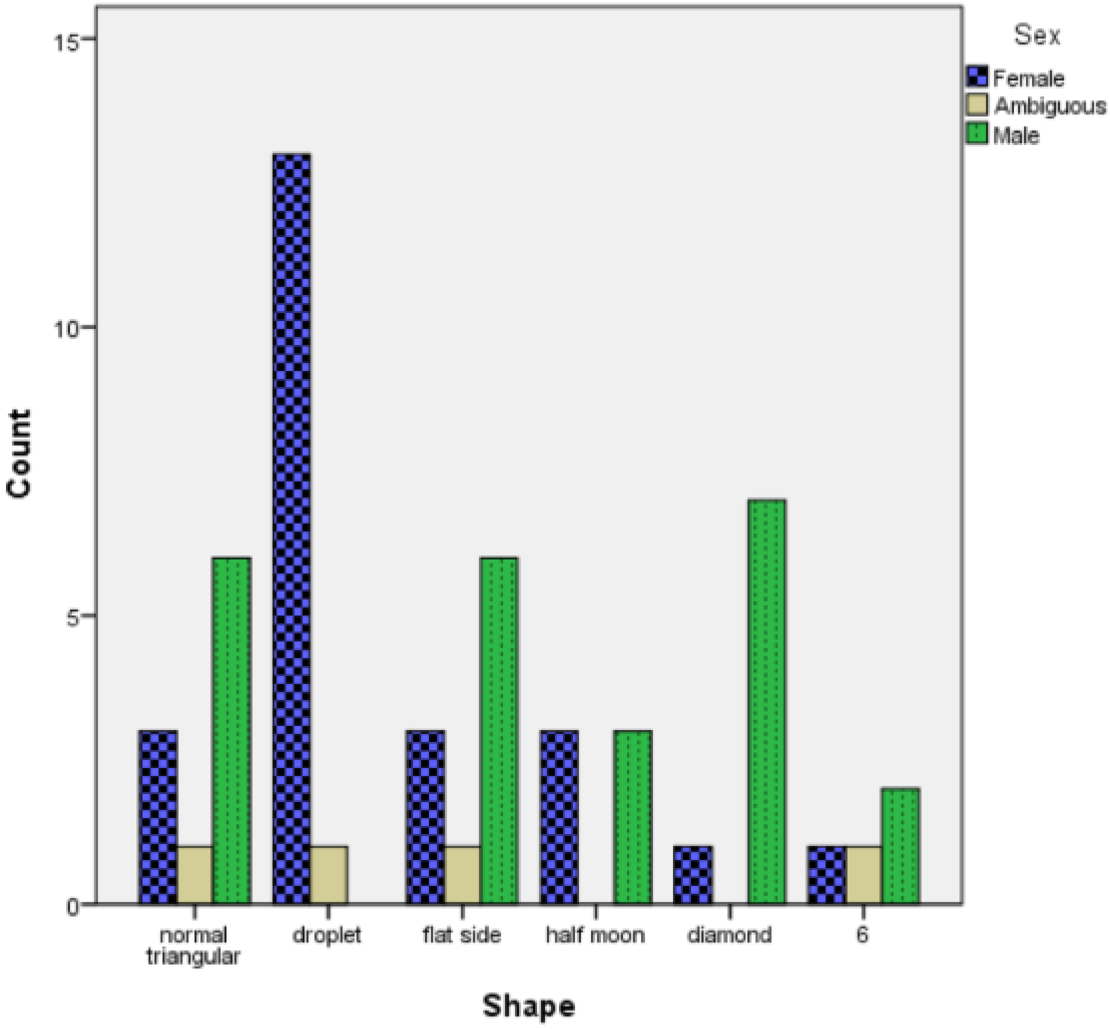


Figure 8.1.22 Bar chart showing shape frequencies at Gabati divided by sex. The most frequently observed shape for females was droplet (n=13), while males are almost evenly divided between triangular (n=6), flat side (n=6), and diamond (n=7).

Tibial intercondylar lengths range from 329 mm to 420 mm – also overall shorter than Jebel Moya, and around the same length as 3-J-18. There is a very clear difference between males and females: males and females only overlap after one standard deviation. The ambiguous/unassigned category fits within the male range. Additionally, the male and female means are close together (382.81 mm vs 354.5 mm), yielding a sexual dimorphism rate of 7.68%. The mean body mass estimate for females is 49.99 kg (±3.35 kg) and for males 55.21 kg (±8.65 kg), yielding a sexual dimorphism rate of 1.9%. This is shown in Figure 8.1.23, and TA is shown in Figure 8.1.24. Female tibiae are shorter than male tibiae, with ambiguous/unassigned closer to the male median and ranges, and female tibiae have lower total area than males, with the upper quartile lower than the male median.

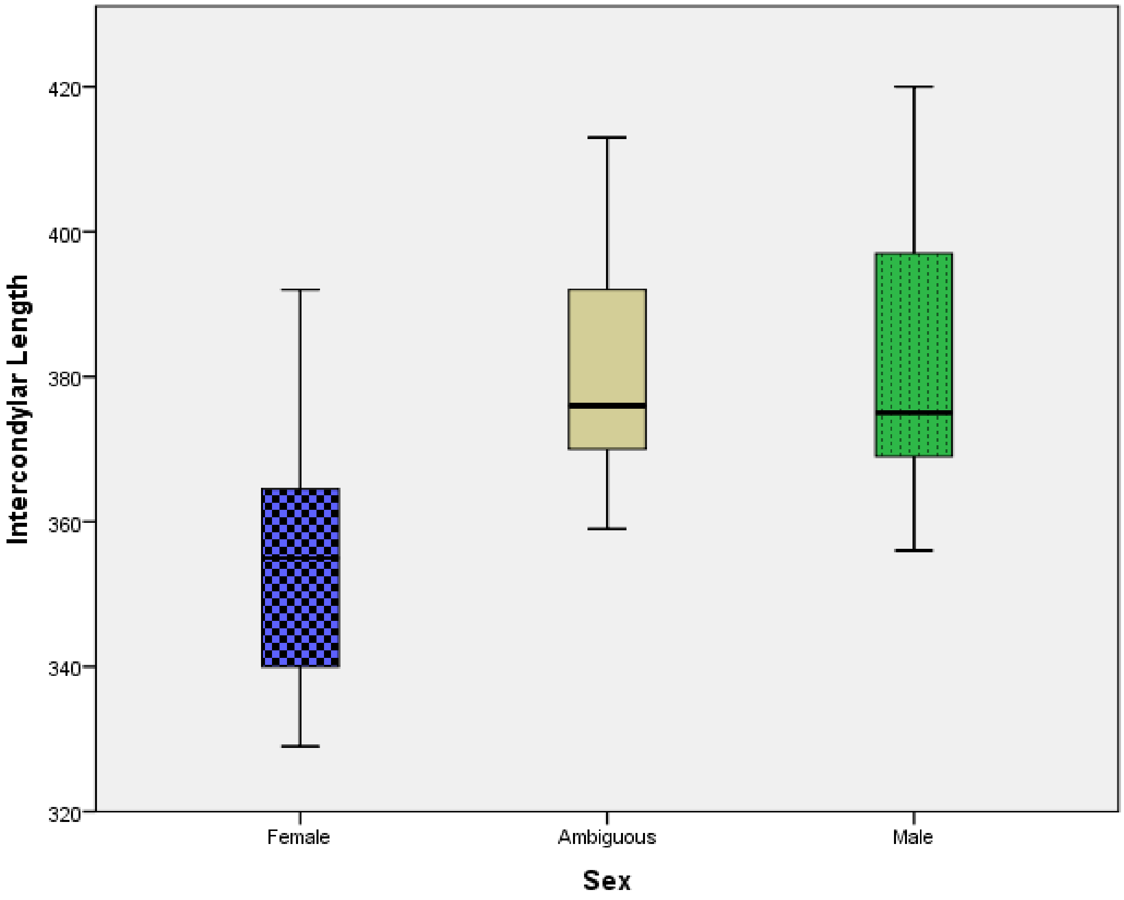


Figure 8.1.23 Boxplot showing tibial intercondylar length by sex at Gabati, units in mm.

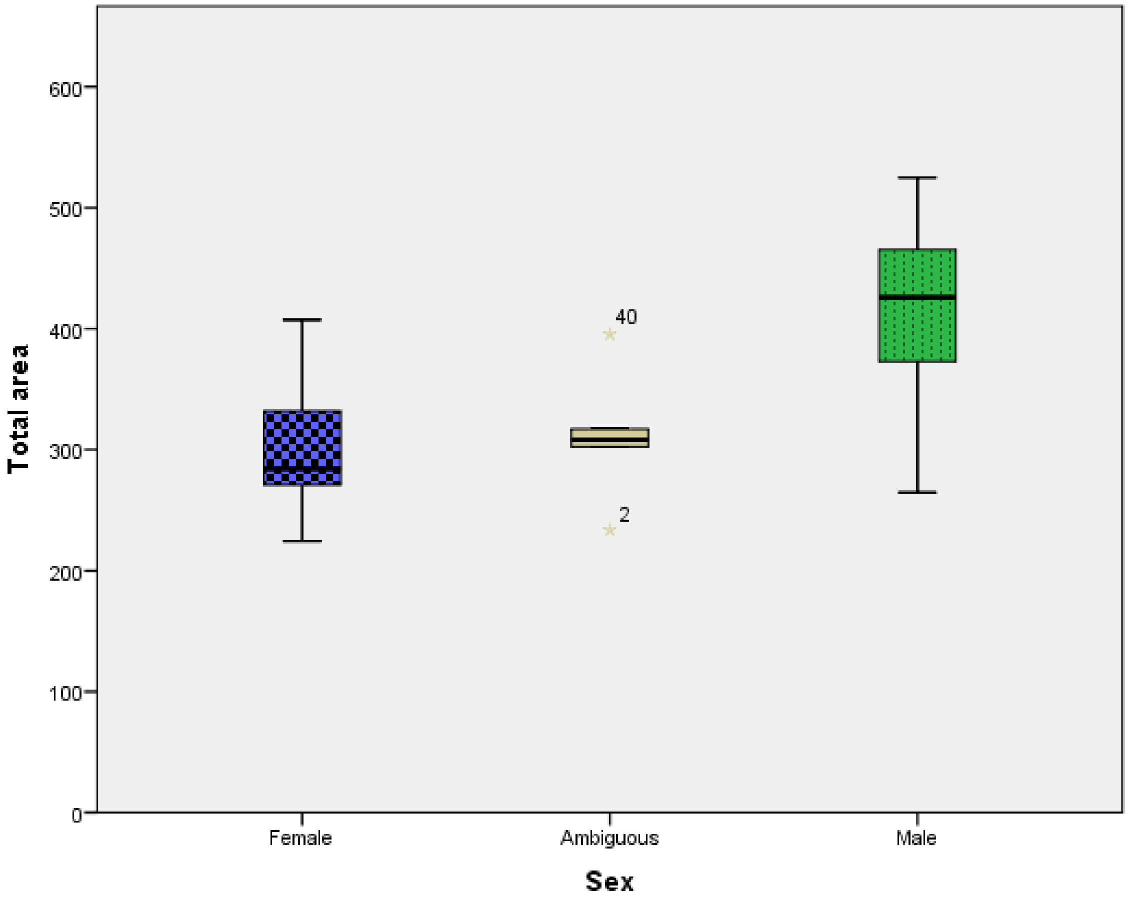


Figure 8.1.24 Boxplot showing total area by sex at Gabati, units in mm^2.

When examining AP and ML diameters at midshaft, males are 1.29% and 1.19% larger in each respective dimension. Compared to 3-J-18, males are larger but females are smaller, shown in Table 8.1.25.

	Females		Males	
	APdiam	MLdiam	APdiam	MLdiam
Mean	22.78	17.786	29.42	21.246
N	15	15	15	15
StdDev	2.339	1.752	2.343	2.503

Table 8.1.25 Female and male AP and ML measurements at Gabati in mm, showing number of individuals and standard deviation.

Using a Student's t-test, differences between males and females were shown to be significant for log length (t=-5.624 with 48 degrees of freedom, p<0.001), log standardised TA (t=-5.128 with 48 degrees of freedom, p<0.001), log standardised J (t=-5.334 with 44 degrees of freedom, p<0.001), log FHD (t=-9.518 with 44 degrees of freedom, p<0.001), log AP diameter (t=-7.712 with 28 degrees of freedom, p<0.001), and log ML diameter (t=-4.533 with 28 degrees of freedom, p<0.001). The sexual dimorphism rates for the log functions are as follows: length, 1.36%; standardised TA, 12.5%; FHD, 3.86%; AP diameter, 8.33%; ML diameter, 6.21%; and standardised *J*, 14.33%.

In summary, these data show the following:

- The most frequently-observed shape for males is diamond and droplet for females
- Length ranges from 329 mm to 420 mm (329-382 mm for females, 256-420 mm for males)
- TA ranges from 210-510 mm^2 (210-402 mm^2 for females, 250-510 mm^2 for males)
- Females are smaller than males in AP diameter by ~3 SDs and in ML diameter by ~2 SDs, with an average dimorphism rate of 7.77%
- Directional asymmetry for two values is not significant
- There are not enough individuals of each sex in each time period to make distinctions based on shape

8.1.5 Chichester

This section discusses the particular frequencies and means of shape, intercondylar length, TA, and midshaft diameters at Chichester.

Frequencies

Chichester, the control site from coastal England, includes 42 individuals: 15 female (35.7%), 18 males (42.9%), and 9 ambiguous/unassigned (21.4%). 12 are assigned to the adult age stage (28.6%), 11 are 20-35 (26.2%), 17 are 35-50 (40.5%), and 2 are 50+ (4.8%). The most frequently observed shape was triangular (18 individuals), then flat side;

interestingly, none are observed to be ovoid. As there are only 42 individuals, it should be noted that statistical tests should be interpreted with caution.

In Chichester, most individuals are triangular (male n=7, female n=8), with flat side observed in the second-highest number of cases for both males and females (n=6, n=4 respectively) and half-moon observed mostly in males (male n=4, female n=1), shown in Table 8.1.26 and Figure 8.1.27. This is the only site with no females observed in the droplet category. The correlation between sex and shape is not significant using a Pearson correlation (r=0.092, n-42, p=0.556), but this should be understood in light of the low number of individuals.

Shape	N	% of Sample
triangular	18	42.90%
droplet	2	4.80%
flat side	13	31.00%
half-moon	5	11.90%
diamond	4	9.50%
ovoid	0	0.00%
Total	42	100%

Table 8.1.26 Shape frequencies at Chichester.

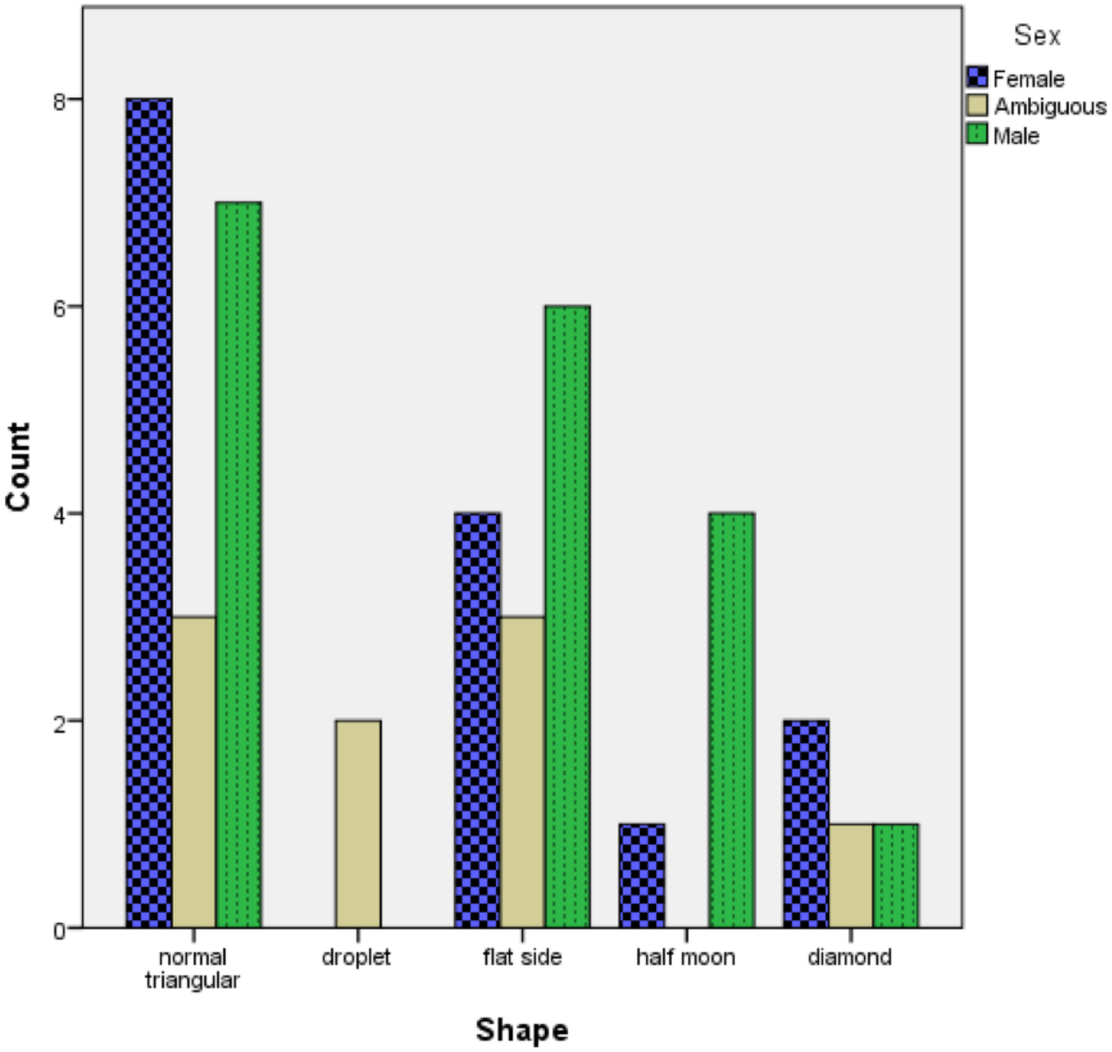


Figure 8.1.27 Bar chart of shape frequencies at Chichester divided by sex.

Means

Individuals at Chichester have overall shorter tibiae than individuals from Sudan, with intercondylar lengths ranging from 297 mm to 400 mm. While male tibiae are longer, there is significant overlap, with the top quartile of females reaching median male lengths. Ambiguous/unassigned individuals fit in between male and female ranges. Mean length for females is 337 mm and mean length for males is 370 mm, yielding a sexual dimorphism ratio of 8.34%. Despite being shorter than the Sudanese sites, individuals at Chichester had greater body mass: the mean body mass estimate for females is 58.16 kg (±4.17 kg) and for males is 70.37 kg (±5.26 kg), resulting in the highest sexual dimorphism rate of 19%.

Intercondylar length is shown in Figure 8.1.28 and TA in Figure 8.1.29. Male tibiae are longer than females, but with overlap in the lower two male quartiles. Males have much greater TA than females, with little overlap.

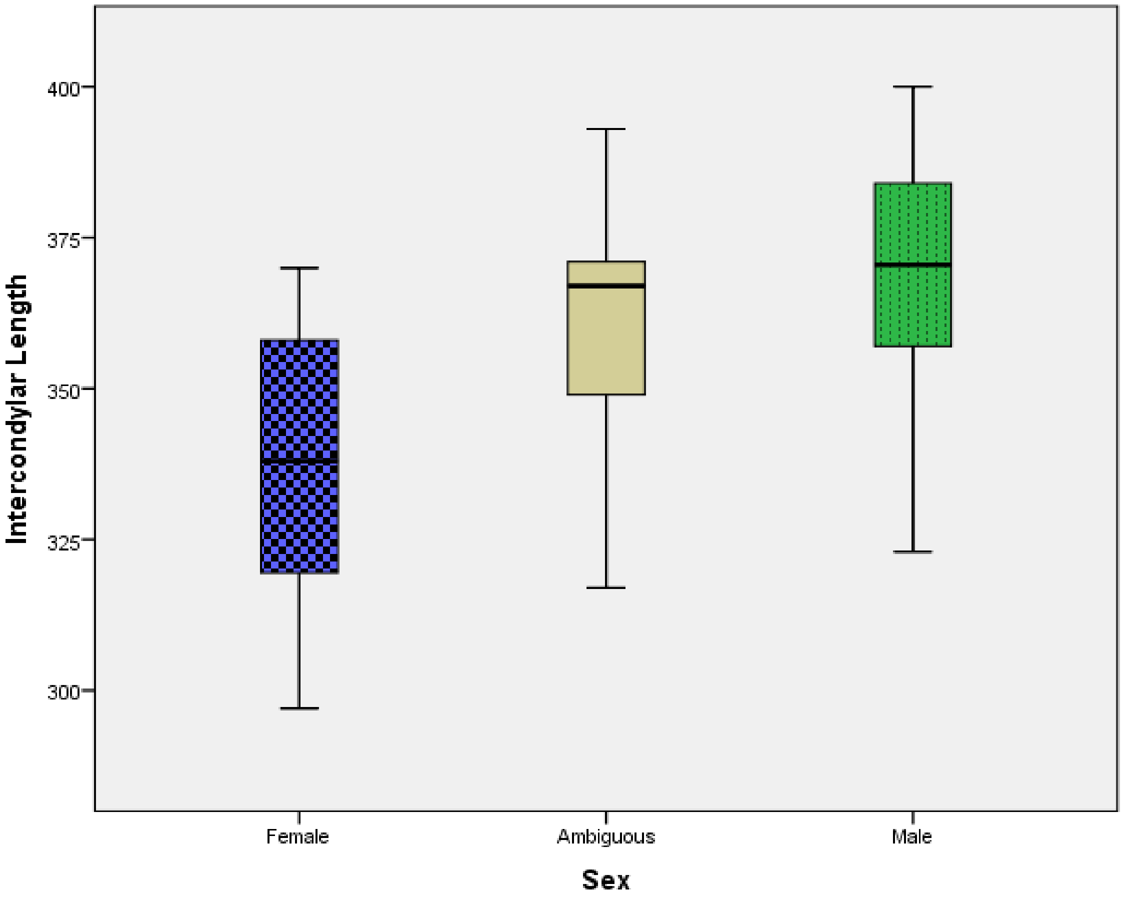


Figure 8.1.28 Boxplot of tibial intercondylar length by sex at Chichester, units in mm.

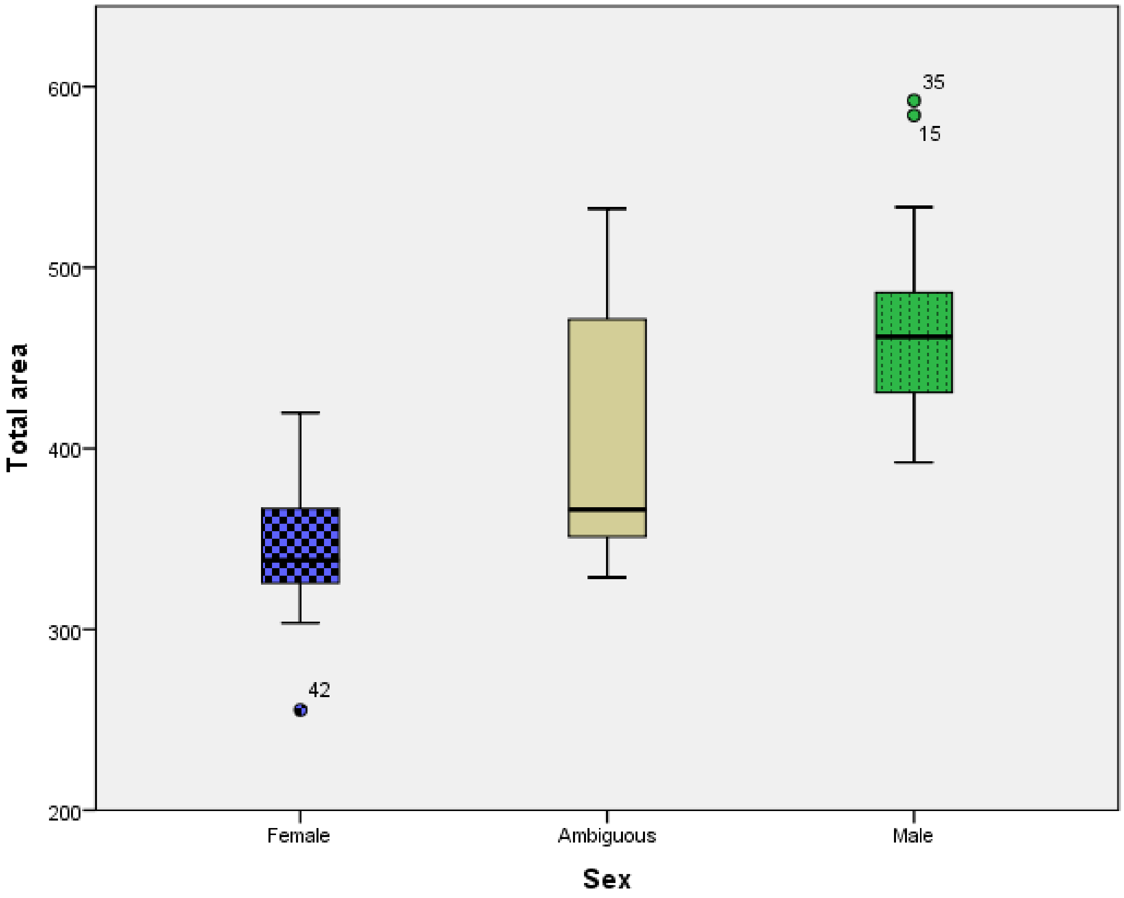


Figure 8.1.29 Boxplot showing total area by sex at Chichester, units in mm^2.

When examining AP and ML diameters at midshaft, males are 1.19% and 1.18% larger in each dimension, respectively, shown in Table 8.1.30. They are approximately equal in dimorphism and actual size to 3-J-18.

	Females		Males	
	APdiam	MLdiam	APdiam	MLdiam
Mean	23.766	18.466	28.444	21.888
N	15	15	18	18
StdDev	2.631	1.836	2.759	1.989

Table 8.1.30 Female and male AP and ML measurements at Chichester in mm.

Using a Student's t-test, differences between males and females were shown to be significant for log length (t=-4.469 with 31 degrees of freedom, p<0.001), log standardised TA (t=-3.165 with 30 degrees of freedom, p<0.001), log standardised *J* (t=-3.214 with 30 degrees of freedom, $p<0.001$), log FHD ($t=-10.267$ with 30 degrees of freedom, $p<0.001$), log AP diameter ($t=-5.028$ with 31 degrees of freedom, $p<0.001$), and log ML diameter ($t=-5.064$ with 31 degrees of freedom, $p<0.001$). The sexual dimorphism rates for the log functions are as follows: length, 1.54%; standardised TA, 7.34%; FHD, 4.3%; AP diameter, 5.69%; ML diameter, 5.84%; and standardised *J*, 7.53%.

In summary, these data show the following:

- The most frequently-observed shape for both males and females is triangular
- Length ranges from 297 mm to 400 mm (297-370 mm for females, 390-400 mm for males, excluding outliers)
- TA ranges from 300-520 mm^2 (300-410 mm^2 for females, 390-520 mm^2 for males)
- Males are larger in diameter by ~1.5 SDs, with an average dimorphism rate of 5.37%

Summary

This section examined shape distribution and size in a number of dimensions (length, anteroposterior and mediolateral diameter, and TA) for the four sites analyzed here. At all sites, female means are smaller than male means for all variables, although there is often overlap – more so in length, where the upper two female quartiles and lower two quartiles of males overlap, than TA, where the overlap is only one quartile of each. Chichester has the highest rate of sexual dimorphism, calculated at 19% for mean body mass. At all sites, the droplet category contained more females than males, and males are over-represented in all shape categories except droplet and triangular. The next section aims to compare all four sites.

8.1.6 Sexual dimorphism and robusticity

This section will briefly summarize sexual dimorphism and robusticity at these sites. As discussed in Chapter 7, sexual dimorphism is calculated here as (male mean-female mean)/female mean *100 for each log value; these values are presented in Table 8.1.31. The highest rate of sexual dimorphism is log standardised *J* at Gabati (14.33%) – rates are high at Gabati for all values tested. The site with the lowest sexual dimorphism is Jebel Moya.

	LnStdJ	LnStdTA	LnFHD	LnLength	LnAP	LnML
Jebel Moya	4.64	3.88	3.23	1.17	3.58	3.96
Gabati	14.33	12.5	3.86	1.36	8.33	6.27
3-J-18	9.23	8.29	3.27	1.19	4.70	3.78
Chichester	7.54	7.34	4.30	1.54	5.69	5.84

Table 8.1.31 Rates of sexual dimorphism in percent at each site for 6 values: log standardised J, log standardised TA, log FHD, log length, log AP diameter, and log ML diameter.

Soleal line robusticity, determined using the Hawkey and Merbs (1995) scale, was examined for each site by sex. Most female tibiae (n=56) were assigned to the “slight” category, with only 20 in “none” and few in the higher categories. The highest number of male tibiae (n=40) were also assigned to “slight”, but had higher numbers of individuals in the three higher categories (n=39, 28, and 11, respectively) and few in “none” (n=7), shown in Figure 8.1.32.

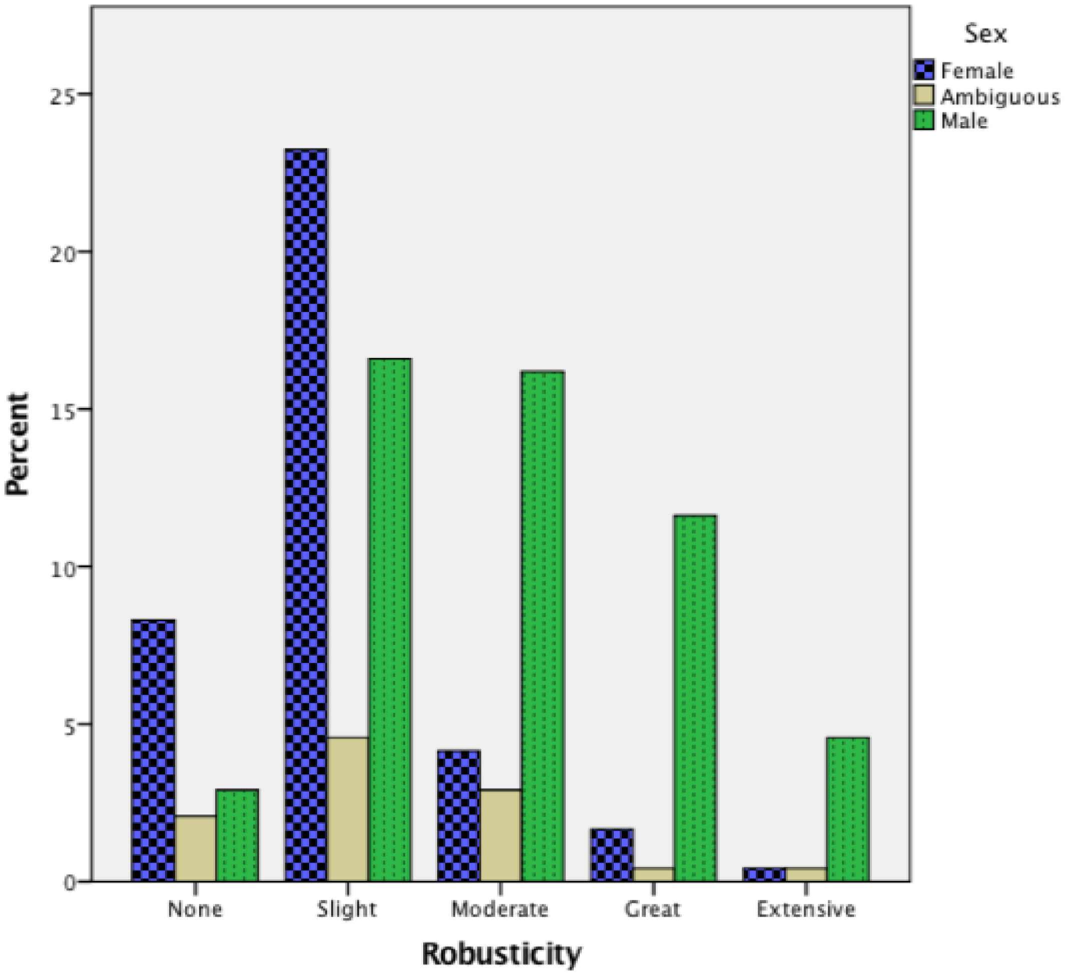


Figure 8.1.32 Bar chart showing the percent of individuals in each robusticity level for males, females, and unassigned/ambiguous.

When examining female tibiae for robusticity by site, all sites follow the pattern seen above. The few females in the "moderate" and "great" groups are mostly from 3-J-18 (n=7), shown in Figure 8.1.33. Site and robusticity are not correlated (Pearson's r=0.062, n=91, p=0.560). Likewise, and excluding those females that could not be assigned to an age stage, robusticity and age appear to be uncorrelated (r=0.128, n=66, p=0.226).

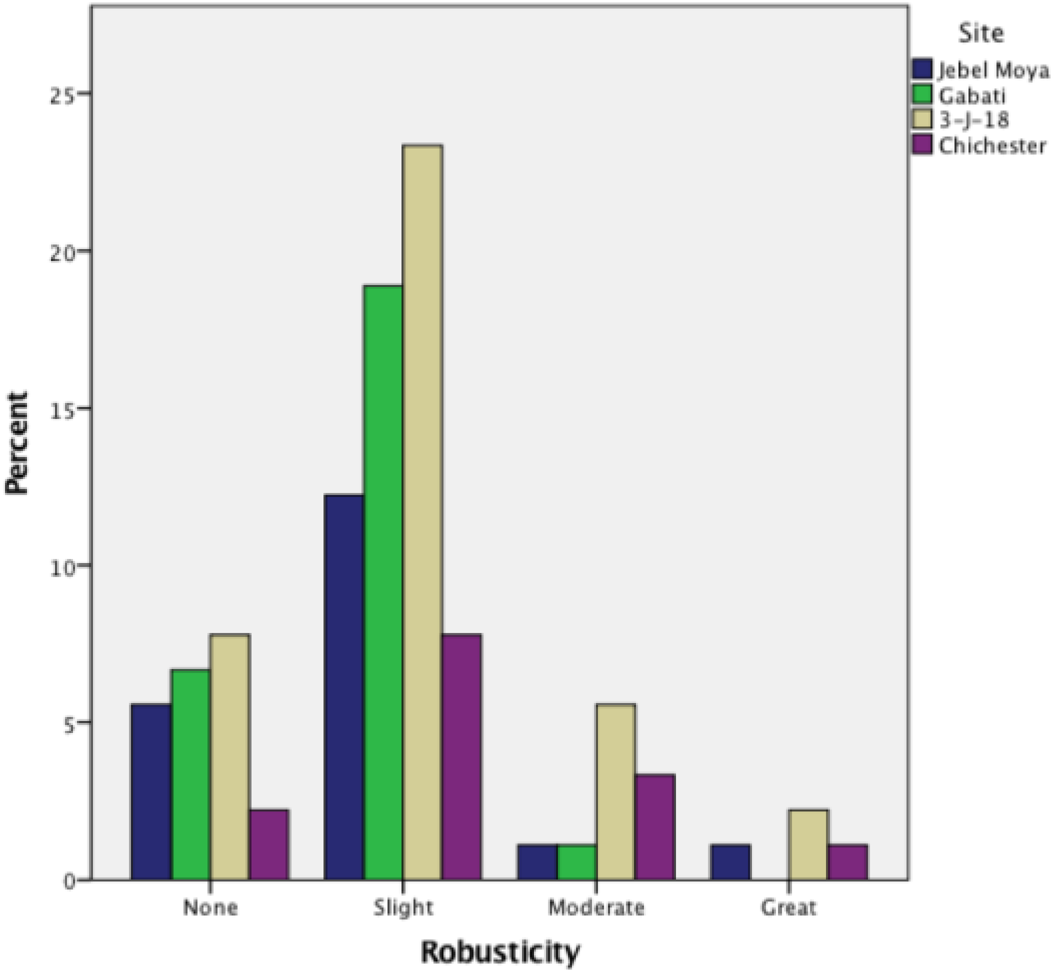


Figure 8.1.33 Bar chart showing the percent of individuals in each robusticity level for females by site.

When examining male tibiae for robusticity by site, there is more variability than with female tibiae. 3-J-18 and Gabati show higher quantities of male tibiae scoring “great”, while Jebel Moya peaks at “slight”, with a decrease of individuals in the higher categories. However, robusticity and site are not correlated using a Pearson correlation (r=0.174, n=125, p=0.174). For males, age was correlated with robusticity excluding the unaged males (r=0.291, n=70, p=0.001), with more middle adult male tibiae assigned to “great” (n=12) and “extensive” (n=7). One older adult male was present in each of those two categories. The unaged males (n=55) show a curve that peaks at slight-moderate (n=20 and 19, respectively).

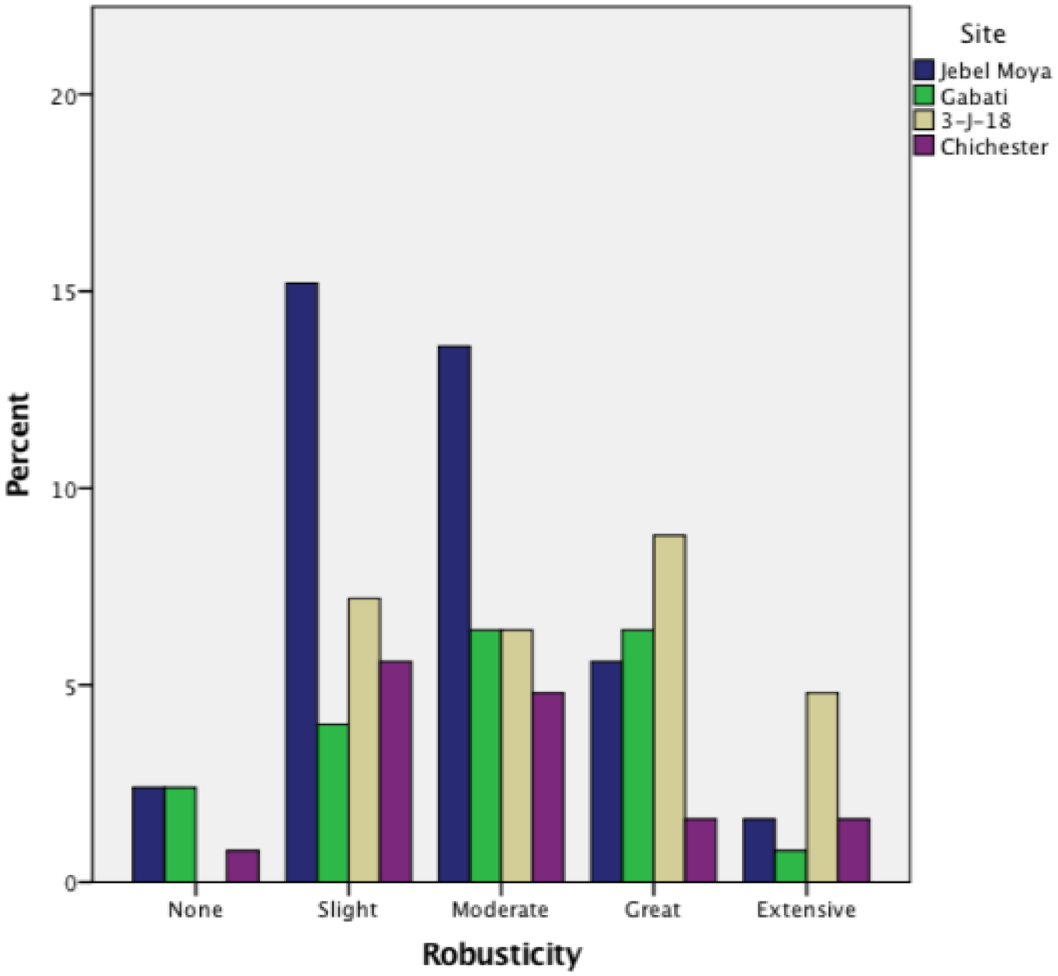


Figure 8.1.34 Bar chart of robusticity levels for males by site.

In summary, the site with the lowest sexual dimorphism is Jebel Moya and the highest is Gabati. Soleal line robusticity peaks at "slight" for females at all sites, while males show different patterns by site; 3-J-18 has the highest average robusticity while Jebel Moya has the lowest. Age was not correlated with robusticity in females, but it was correlated for males.

8.2 Cross-sectional geometry

This section displays the results of cross-sectional geometric (biomechanical) analyses, showing variation in bending strength, torsional strength, and robusticity. While focusing on the cross-sectional geometric properties discussed in previous chapters (TA, *J*, and second moments of area), shape variation is also considered in relation to these properties. TA and J were standardized using the equations presented in Chapter 7.4.2. Estimated body mass was based on the femoral head diameter, using equations for each sex developed by Ruff (1991), shown in Chapter 7.2.3. As some individuals did not have an extant femoral head (from either side), body mass could not be estimated. For individuals of ambiguous/unknown sex, the $BM_{combined}$ equation was used.

All tests were conducted using SPSS.

8.2.1 Summary statistics

Table 8.2.1 below shows summary statistics for each CSG value, separating males and females (ambiguous/unassigned are excluded). The upper box shows standardised TA and standardised *J*; the middle box TA and J; and the lower box I_{max}/I_{min} and I_x/I_y.

Assem.	Males	N	Females	N

	StTA		StJ			StTA		StJ		
	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Jebel Moya	8.24	1.74	46.976	9.724	48, 29	7.906	0.77	39.789	7.937	12, 20
3-J-18	7.15	0.699	35.196	5.395	38, 40	6.147	0.756	26.431	5.55	38
Gabati	6.776	1.84	37.987	11.5	26, 24	5.38	1.84	24.041	6.844	24, 22
Chiches	6.695	0.62	41.581	8.279	18	5.518	1.71	32.166	6.955	15, 14
	TA		J			TA		J		
	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Jebel Moya	545.266	74.44	54042.24	15235	46	446.055	66.734	35196.44	10831	20
3-J-18	425.53	51.024	32404.98	7279.3	40	330.99	43.315	19090.8	4956.3	38
Gabati	411.943	64.04	31252.16	9407.4	26	298.942	46.718	15669.5	5014/34	24
Chiches	471.054	56.596	40133.21	9859.4	18	344.768	39.938	21351.44	5139.6	15
	Imax/Imin		Ix/Iy			Imax/Imin		Ix/Iy		
	Mean	SD	Mean	SD	N	Mean	SD	Mean	SD	N
Jebel Moya	2.158	0.401	1.647	0.38	46	2.007	0.2933	1.7403	0.229	20
3-J-18	2.2003	0.369	1.391	0.316	38	1.9069	0.2582	1.2627	0.2782	38
Gabati	2.253	0.37	1.456	0.393	26	1.924	0.432	1.195	0.222	24
Chiches	2.017	0.359	1.343	0.241	18	2.007	0.386	1.339	0.454	15

Table 8.2.1 Summary statistics of standardised TA (StTA), standardised J (StJ), TA, J, I_{max}/I_{min}, and I_x/I_y for males and for females at each of the four sites. The mean and standard deviation (SD) are given for each. The number of individuals (N) used in each analysis is shown.

8.2.2 Total area (TA)

Figures 8.2.2. and 8.2.3 show boxplots of total area and standardised total area by site and sex. Total area is a correlate of compressive strength. Jebel Moya has consistently higher values for TA. All sites feature higher TA values for males than females (ambiguous/unassigned individuals are not shown, and are all in between, as is expected given that they are probably a mix of males and females). Also note the outlier males labelled 141, 136, and 21: the latter two have intercondylar length and femoral head diameter measurements more associated with females in these groups, so perhaps assessing sex using only the pelvis does not provide a holistic image of the individual's sex, or perhaps there is more variation in sexual dimorphism than expected. While the 3-J-18, Gabati, and Chichester female TA values reach a maximum of around 400 mm^2, while Jebel Moya females reach or even exceed the values of males at all the other sites. Gabati has the smallest TA values for both males and females, with a value of 264 mm^2 and 224 mm^2, respectively.

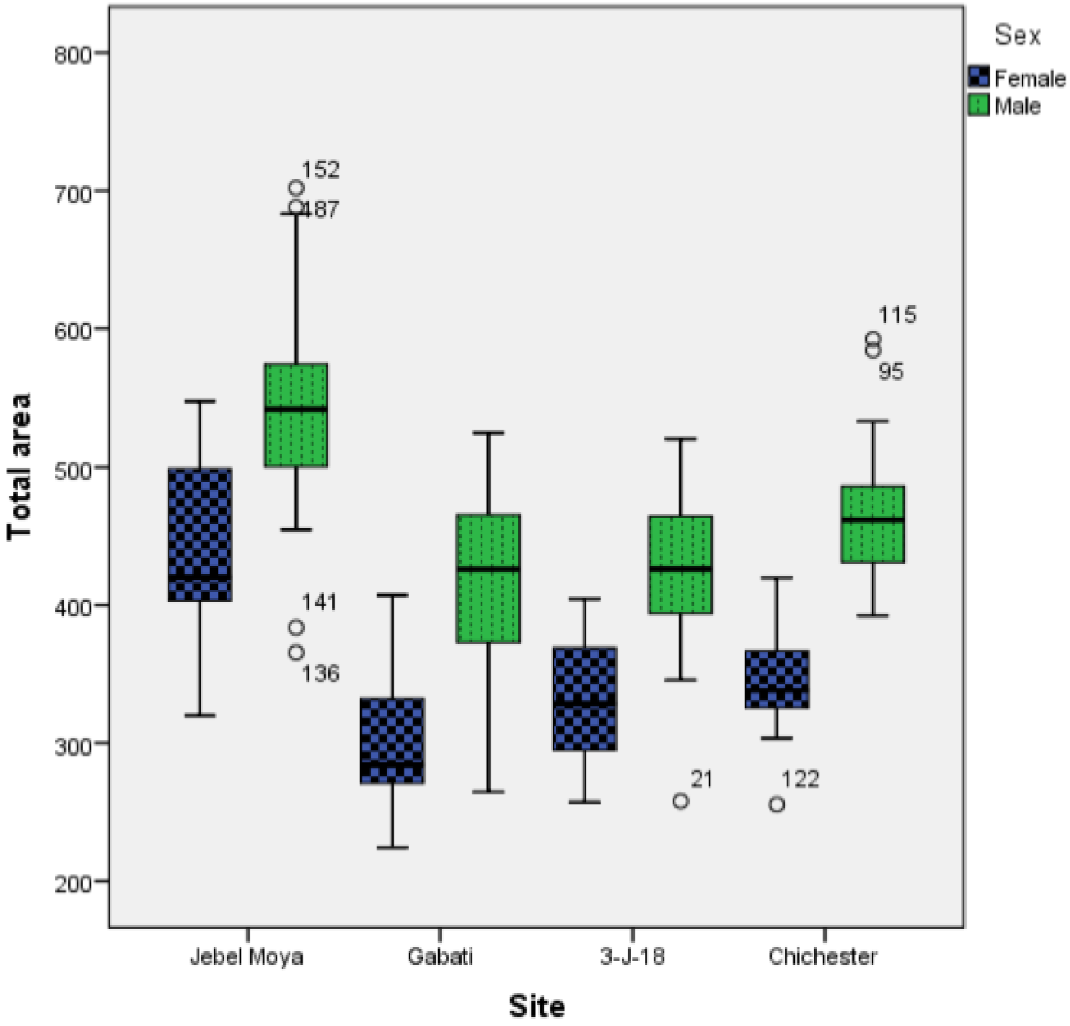


Figure 8.2.2 Boxplot showing total area median and rages for males and females by site, units in mm^2.

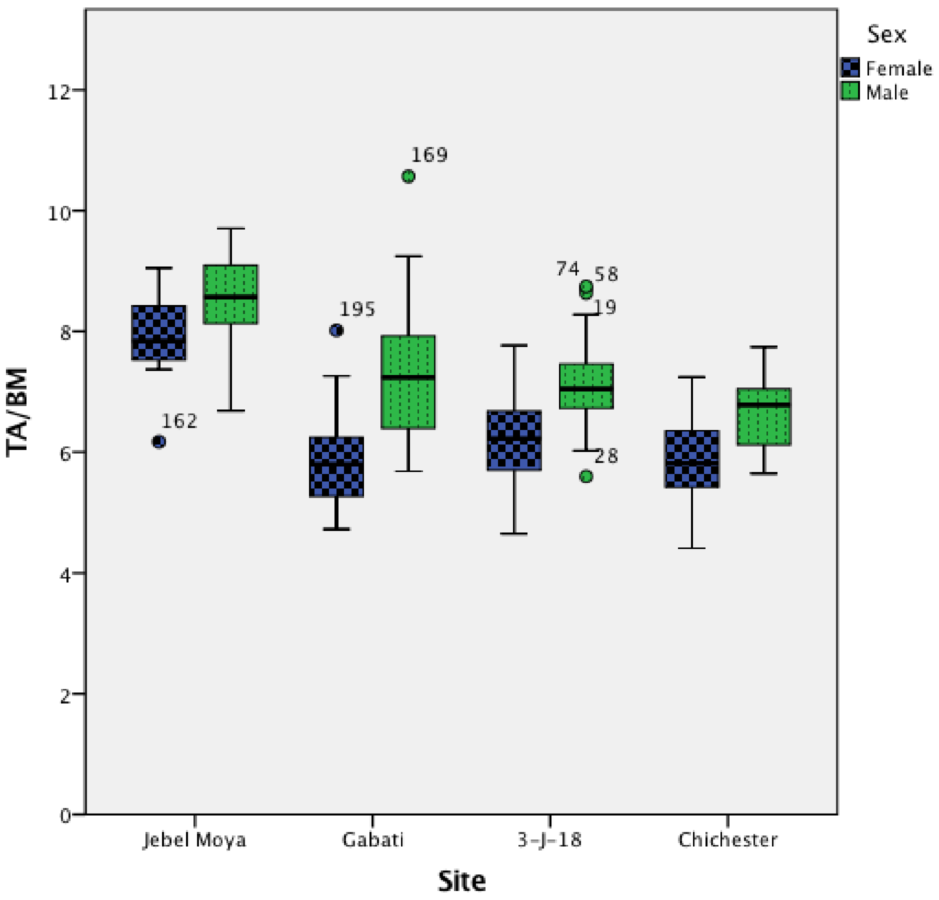


Figure 8.2.3 Boxplot showing median and ranges of standardised total area (calculated as total area divided by estimated body mass) for males and females by site.

When standardised for body size, only Jebel Moya's top two quartiles can be considered as only 29 (41%) of individuals have measurable femoral heads. Jebel Moya still presents higher values, although more equally distributed between males and females: controlling for body size eliminates the sheer size advantage of the Jebel Moya males, though they are still the greatest in TA. When examined in a scatter plot to reveal individual values, it is clear that those (from each site) without femoral heads to standardise body size cluster around 0, shown in Figure 8.2.4.

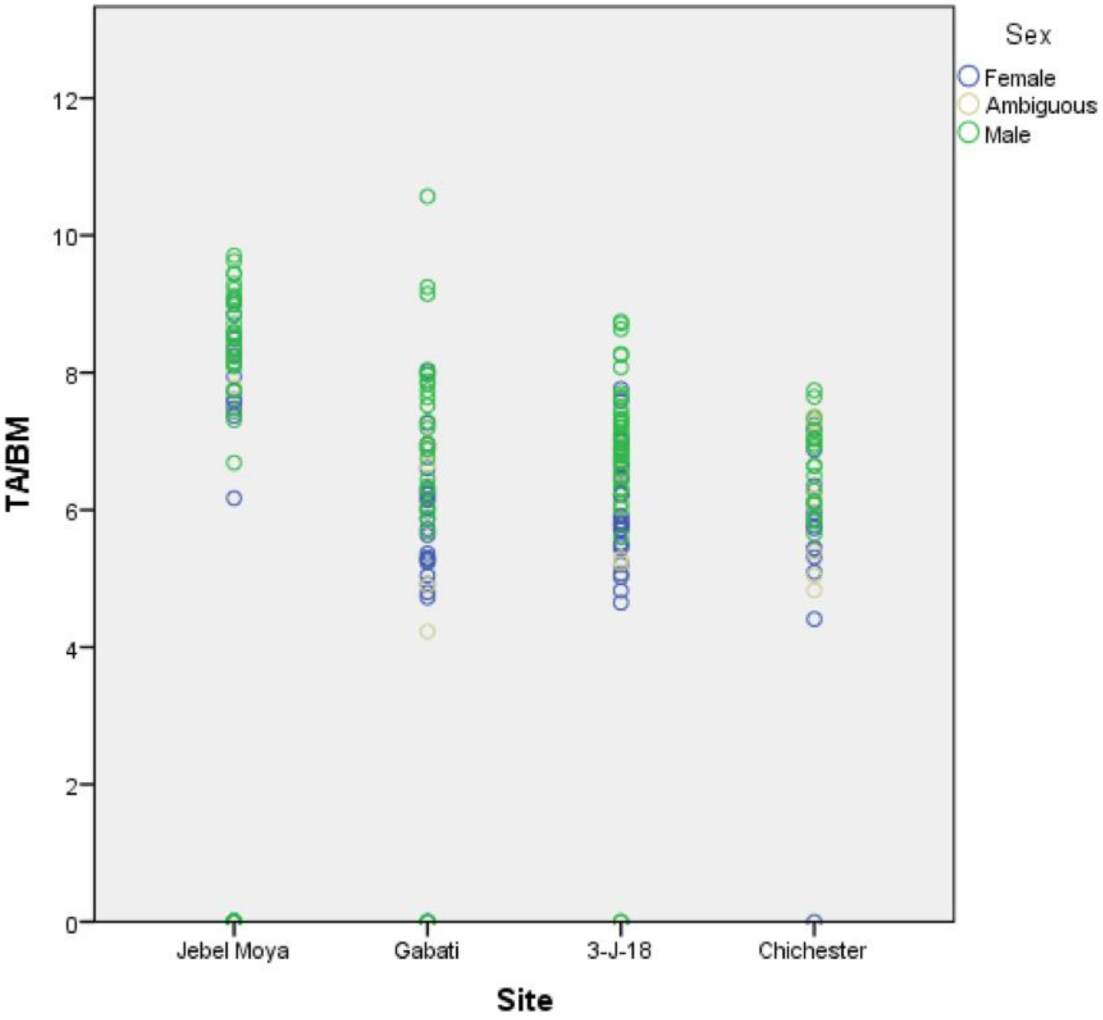


Figure 8.2.4 Scatter plot comparing site with standardised TA to reveal the error in the lower two quartiles of Figure 8.2.3.

A one-way ANOVA was conducted on the data to test for significant differences between TA at each site. TA, not standardised TA, was used as the standardised TA revealed significant outliers and Jebel Moya would have to be excluded, as shown above in Figure 8.2.4. First, Levene's test for homogeneity of variance was conducted: the difference in TA between sites was found to be significant for females (p=0.015) but not for males. Thus in addition to an ANOVA a Tukey post-hoc test was performed for females and a Welch post-hoc test for males, which showed that despite nonhomogeneity of variance, the differences are still significant (female F(3,93)=35.729, p<0.001; male F(3,126)=35.315, p<0.001). There was a statistically significant difference between TA when comparing Jebel Moya to the three other sites, as well as when comparing Gabati and Chichester. Differences in TA are not significant between 3-J-18, Gabati, and Chichester for either males or females. So far, this indicates a similarity between three agricultural and/or sedentary groups. The results of the ANOVA are shown stepwise in Table 8.2.5 and specific p-values from the Tukey's post hoc for each comparison are shown in Table 8.2.6.

TA	Significance Jebel Moya compared with			3-J-18 compared with		Gabati compared with
	3-J-18	Gabati	Chichester	Gabati	Chichester	Chichester
Female						
Mean Dif	115.065	147.113	101.287	32.048	-13.777	-45.826
Std Error	13.635	14.943	16.858	12.869	15.05	16.245
P-value	<0.005	<0.005	<0.005	0.068	0.797	<0.005
Male						
Mean Dif	119.736	133.323	74.211	13.586	-45.524	-59.111
Std Error	13.762	15.577	17.651	15.994	18.02	19.467
P-value	<0.005	<0.005	<0.005	0.831	0.029	0.015

Table 8.2.5 Results of an ANOVA comparing each site based on TA, divided by sex, showing mean difference, standard error, and p-value for intersite comparisons.

Females	Jebel Moya	3-J-18	Gabati	Chichester	**Males**	Jebel Moya	3-J-18	Gabati	Chichester
Jebel Moya		<0.005	<0.005	<0.005	Jebel Moya		<0.005	<0.005	<0.005
3-J-18	<0.005		0.068	0.797	3-J-18	<0.005		0.831	0.029
Gabati	<0.005	0.068		0.029	Gabati	<0.005	0.831		0.015
Chichester	<0.005	0.797	0.029		Chichester	<0.005	0.061	0.015	

Table 8.2.6 P-values from the Tukey's post hoc test for the ANOVA shown in Table 8.2.5 for ease of comparison.

An additional ANOVA was conducted to test significant differences between shape categories by TA ($F(5,242)=12.283$, $p<0.001$): there are a number of significant differences in each category, shown in Table 8.2.7. Droplet is significantly different from all other categories, while triangular, flat side, half-moon, and diamond are more alike. This is further illustrated as a boxplot in Figure 8.2.8. Droplet has the lowest total area of all categories, at 330.44 mm^2 (±63.72 mm^2). The highest was diamond, at 489.2 mm^2 (±84.92 mm^2). Droplet has the lowest median TA and diamond has the highest. Triangular, flat side, and half-moon are roughly equal, shown in Figure 8.2.8. A one-way ANOVA with Tukey's post hoc determined the difference between groups was significant (p<0.001).

Shape	Triangular	Droplet	Flat side	Half-moon	Diamond	Ovoid
Triangular		<0.005	0.559	0.397	0.001	1
Droplet	<0.005		<0.005	<0.005	<0.005	0.012
Flat side	0.559	<0.005		0.988	0.082	0.916
Half-moon	0.397	<0.005	0.988		0.52	0.749
Diamond	0.001	<0.005	0.082	0.52		0.046
Ovoid	1	0.012	0.916	0.749	0.046	

Table 8.2.7 Significance levels from the Tukey's post-hoc for the ANOVA testing differences between shapes by TA.

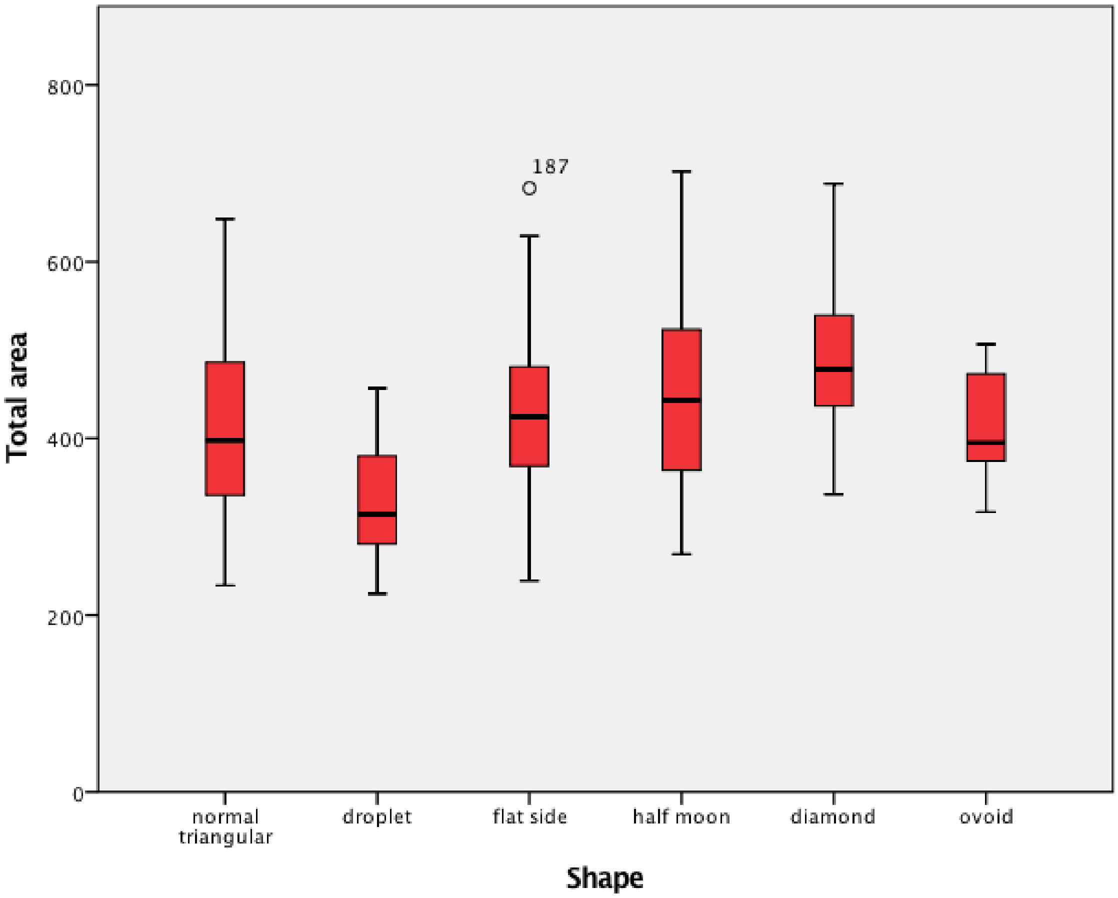


Figure 8.2.8 Boxplot showing shape categories and total area for all individuals.

Summary

TA, even when adjusted for body mass, is always higher in males than in females. It is highest overall at Jebel Moya; the other sites are more similar to each other, leading towards a conclusion of similar TA (adjusted and unadjusted) occurring within agricultural communities and a possible link between higher presumed mobility and higher TA – that is, individuals who are highly mobile have higher compressive strength than those who are less mobile. When compared with shape, droplet is significantly different in TA than the others: droplet-shape tibiae are considerably lower in TA. As discussed in section 8.1 above, the droplet shape could be the result of lower mobility, and thus would be expected to have lower TA.

8.2.3 Polar second moment of area (*J*)

Figures 8.2.9 and 8.2.10 display boxplots of the raw and standardised values for *J*, a correlate of torsional rigidity. Again, Jebel Moya has much higher values for *J*, indicating greater resistance to torsional stress. Particularly notable are the Jebel Moya females, which have approximately the same mean value as males from the other three sites (35196.444 mm^4 ± 10831.185); however, the lowest quartile of Jebel Moya females overlaps with the highest two quartiles of females at the other sites. Males and females at Chichester have higher means than Gabati and 3-J-18.

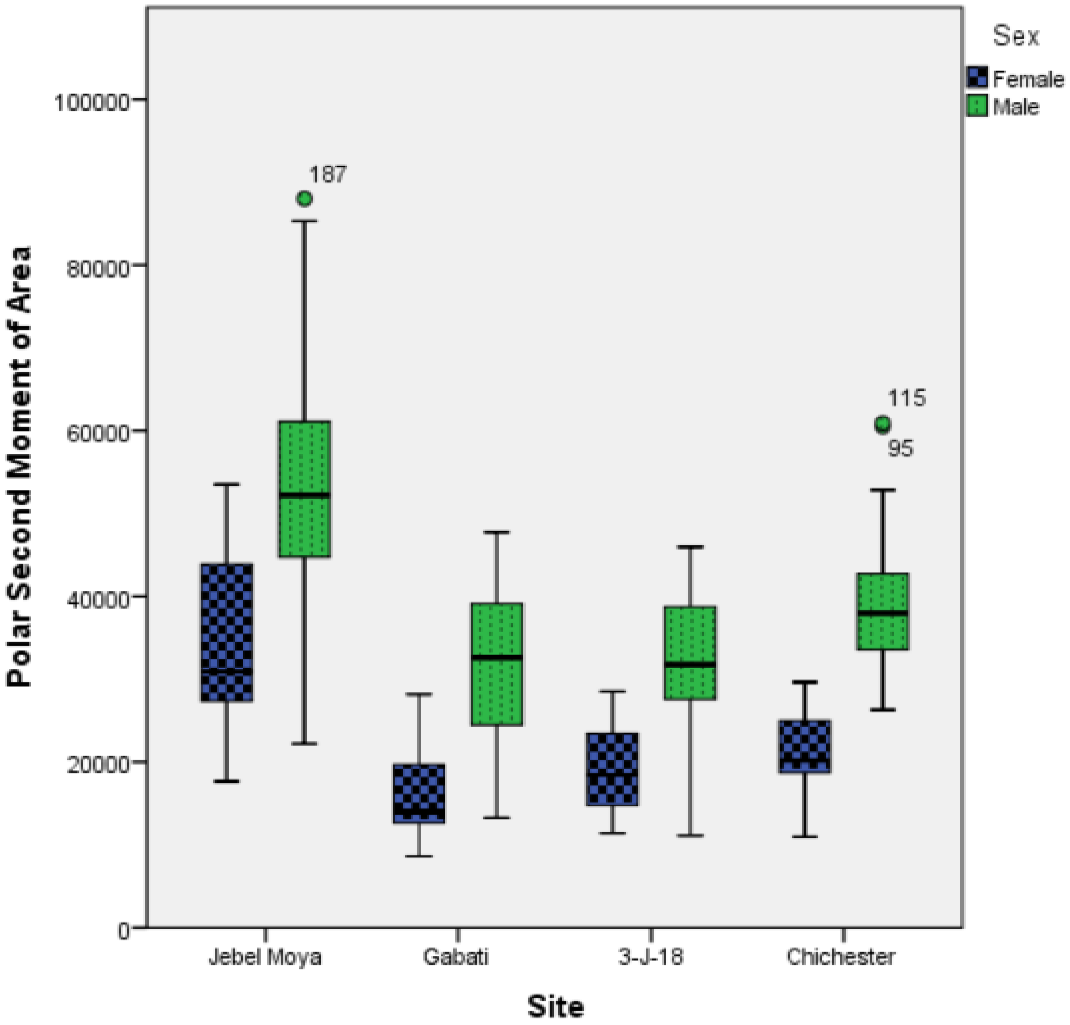


Figure 8.2.9 Boxplot showing polar second moment of area for males and females by site.

When standardised for body size, the Jebel Moya males still have much higher values, but not multiple standard deviations higher as in the non-standardised *J* values. Standardising has clarified why the Jebel Moya males have such a large range for *J*: they have the largest range for tibial intercondylar length. The shortest tibia in Jebel Moya (360 mm) actually belongs to a skeleton sexed as male; however, the individual outliers (labelled 136 and 138) are not the shortest in length – both are within the upper two quartiles for male tibial intercondylar length, showing that *J* values are not directly associated with overall length. Likewise, the Gabati male labelled 195 is not the tallest: that outlier is in the lowest quartile for intercondylar length. Testing only males, the relationship between intercondylar length and standardised *J* was not significant (p=0.15), and was shown to be even less significant when an ANOVA was conducted on length quartiles (F(3,250)=3.757, p=0.011): this is illustrated in the boxplot in Figure 8.2.9. (The relationship between non-standardised J and length is significant as expected, because as length increases mass and thus *J* increase – hence why standardization is necessary.) The relationship was similarly nonsignificant for females. A scatterplot showing the lack of correlation between non-standardised *J* and length is shown in Figure 8.2.11.

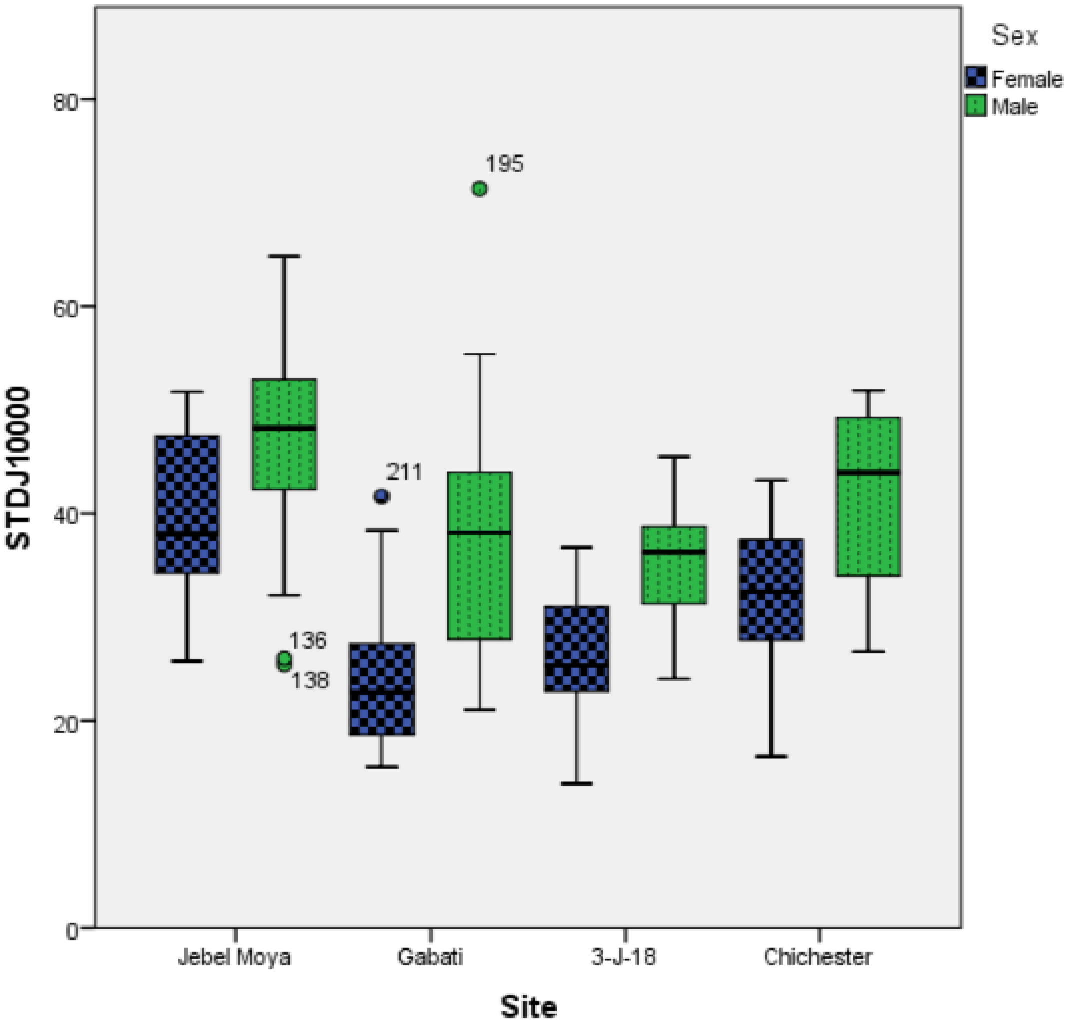


Figure 8.2.10 Boxplot showing standardised polar second moment of area (calculation shown above) for males and females by site.

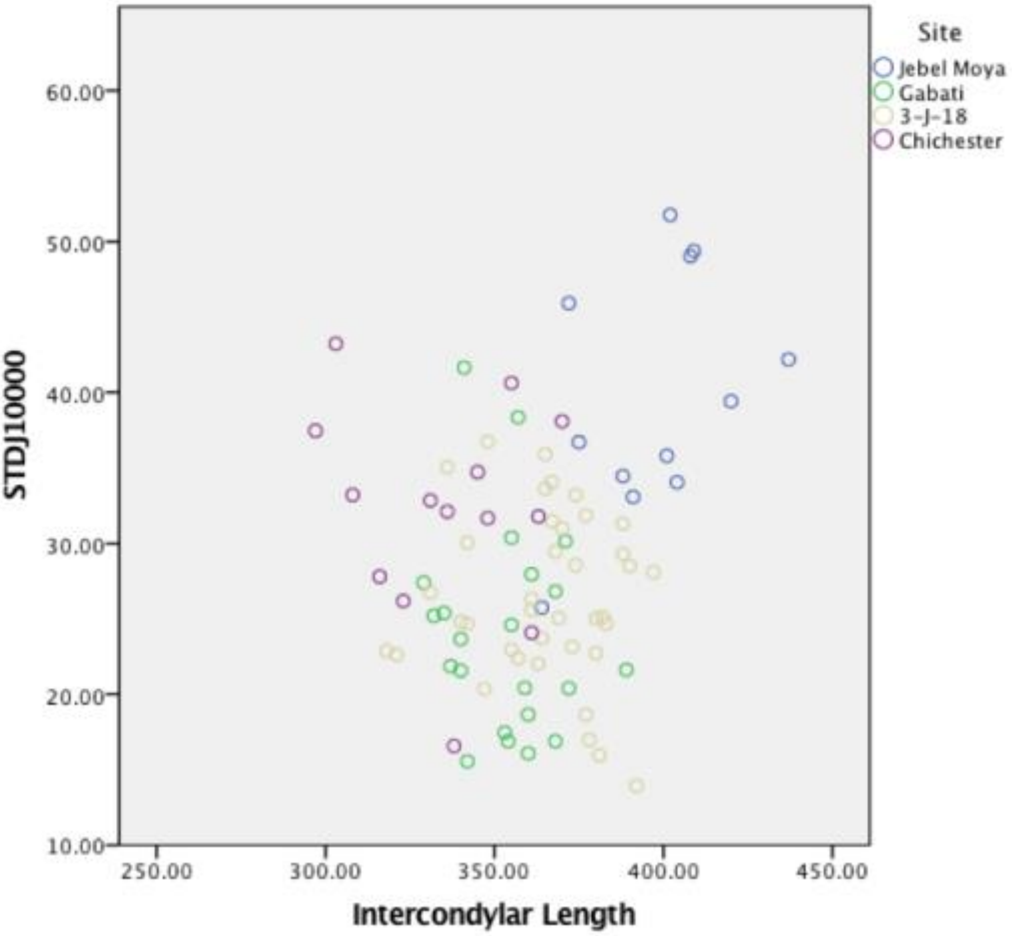


Figure 8.2.11 Scatterplot of standardised polar second moment of area by tibial intercondylar length for females only (male scatter plot showed similar). Length units in mm, *J* in mm^4.

A one-way ANOVA was conducted on the data to test for significant differences in *J* between each site. Standardised *J* was used and the one significant outlier was excluded. A Levene's test of homogeneity of variance was conducted: the difference in standardised J between sites was found to be significant for males (p=0.04) but not for females. Thus in addition to an ANOVA a Tukey post-hoc test was performed for males and a Welch post-hoc test for females, which showed that despite nonhomogeneity of variance, the differences are still significant (female F(3,93)=1.609, p=0.193; male F(3,128)=3.239, p=0.024). Note that this is the opposite of the ANOVA results for TA, above. Differences between Jebel Moya and the other three sites are significant for females; the only nonsignificant figure was the difference between 3-J-18 and Gabati. For males, only the differences between Jebel Moya, 3-J-18, and Gabati are significant. There are overall fewer significant differences for standardised J than for TA. The results of the ANOVA are shown stepwise in Table 8.2.12 and specific p-values for each comparison are shown in Table 8.2.13.

J	Significance					
	Jebel Moya compared with			3-J-18 compared with		Gabati compared with
	3-J-18	Gabati	Chichester	Gabati	Chichester	Chichester
Female						
Mean Dif	13.358	15.748	7.623	2.39	-5.735	-8.125
Std Error	2.147	2.327	2.551	1.737	2.027	2.217
P-value	<0.005	<0.005	0.019	0.518	0.029	0.002
Male						
Mean Dif	11.779	10.439	5.397	-1.34	-6.384	-5.044
Std Error	2.012	2.273	2.44	2.134	2.311	2.542
P-value	<0.005	<0.005	ns	ns	ns	ns

Table 8.2.12 Results of an ANOVA comparing each site based on J, divided by sex, showing mean difference, standard error, and p-value for intersite comparisons. NS=not significant.

Females	Jebel Moya	3-J-18	Gabati	Chichester	**Males**	Jebel Moya	3-J-18	Gabati	Chichester
Jebel Moya		<0.005	<0.005	0.019	Jebel Moya		<0.005	<0.005	0.127
3-J-18	<0.005		0.518	0.029	3-J-18	<0.005		0.923	0.034
Gabati	<0.005	0.518		0.002	Gabati	<0.005	0.923		0.201
Chichester	0.019	0.029	0.002		Chichester	0.127	0.034	0.201	

Table 8.2.13 P-values from the Tukey's post-hoc for the ANOVA shown in Table 8.2.12 for ease of comparison.

An additional ANOVA with Tukey's post hoc determined the difference between groups by *J* was significant (F(5,91)=1.39, p<0.001): there are a number of significant differences in each category, shown in Table 8.2.14. Once again the droplet category is significantly different from the other five categories, while triangular, flat side, half-moon, and ovoid are not significantly different from each other. Figure 8.2.15 illustrates how *J* values show a large difference between shape categories. Droplet has the lowest *J* values while diamond has the highest median, half-moon has the highest overall value and the greatest range. The diamond category had the highest mean, at 44359.29 mm^4 (±16144.71) and again the droplet had the lowest at 19116.68 mm^4 (±7537.37). The means of the other categories are within 30000-40000 mm^4. Standardised J produced equivalent results, not shown here.

Shape	Triangular	Droplet	Flat side	Half-moon	Diamond	Ovoid
Triangular		0.007	0.128	0.306	<0.005	0.63
Droplet	0.007		<0.005	<0.005	<0.005	0.001
Flat side	0.128	<0.005		1	0.006	1
Half-moon	0.306	<0.005	1		0.052	1
Diamond	<0.005	<0.005	0.006	0.052		0.038
Ovoid	0.63	0.001	1	1	0.038	

Table 8.2.14 P-values from the Tukey's post-hoc for the ANOVA comparing shape categories by J.

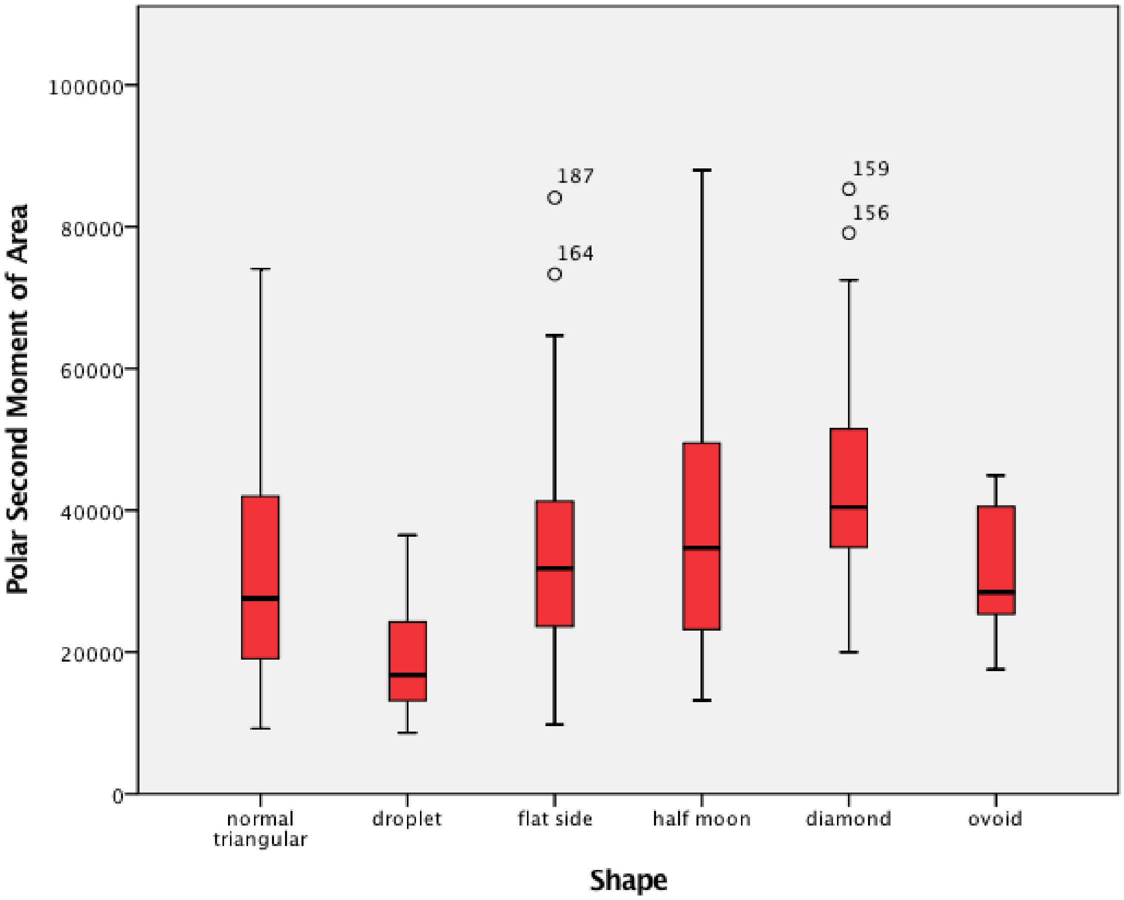


Figure 8.2.15 Boxplot showing shape categories and *J* for all individuals. *J* units in mm^4.

Summary

J, as expected, closely models TA. Even when adjusted for body mass, it is always higher in males than in females. It is highest overall at Jebel Moya, particularly for males, who span a large range that may be inaccurate based on poor sexing by previous researchers and damage to the collections. Like with TA, the other sites are more similar to each other, leading towards a conclusion of similar J (standardised and non-standardised) occurring within agricultural communities and, again, a possible link between higher presumed mobility and higher TA. As J is correlated with torsional strength, it can be tentatively concluded that those individuals or groups with high compressive strength (TA) also have high torsional strength (J). When compared with shape, the droplet shape is significantly different in J than the others: droplet-shape tibiae are considerably lower in J values and thus lower in torsional strength.

8.2.4 Second moment of area in the maximum and minimum planes (I_{max}/I_{min})

I_{max}/I_{min} is an indicator of circularity and a correlate of bending rigidity. As it is a ratio, it does not need to be standardised. When examining the boxplot of all sites shown in Figure 8.2.16, there appears to be more equality of both range and distribution between the sites and the sexes. For this reason, males and females will be compared to each other as well as overall sex-independent comparisons. The mean I_{max}/I_{min} for females is 1.947 (SD=0.333) and the mean I_{max}/I_{min} for males is 2.164 (SD=0.382); combined, it is 2.069 (SD=0.383). Again, the closer to 1, the more circular the cross-section, although it is important to keep in mind that the tibia will never actually reach 1 (unlike potentially the femur or humerus) as it is at best triangular in cross-section. The highest overall I_{max}/I_{min} is seen in a male from Jebel Moya (3.63) and the lowest is seen in a female from Gabati (1.36). Examining the shape categories, the male with the highest I_{max}/I_{min} is ovoid and the female with the lowest I_{max}/I_{min} is triangular. A two-way ANOVA shows that while the difference in I_{max}/I_{min} is significantly different between sexes (F(2,240)=6.82, p=0.01), it is not significantly different between sites (F(3,240)=1.11, p=0.344) or between sex and site (F(6,240)=1.44, p=0.2), confirmed by a Tukey's post-hoc test (female-ambiguous p=0.473; female-malep<0.001; male-ambiguous p=0.301).

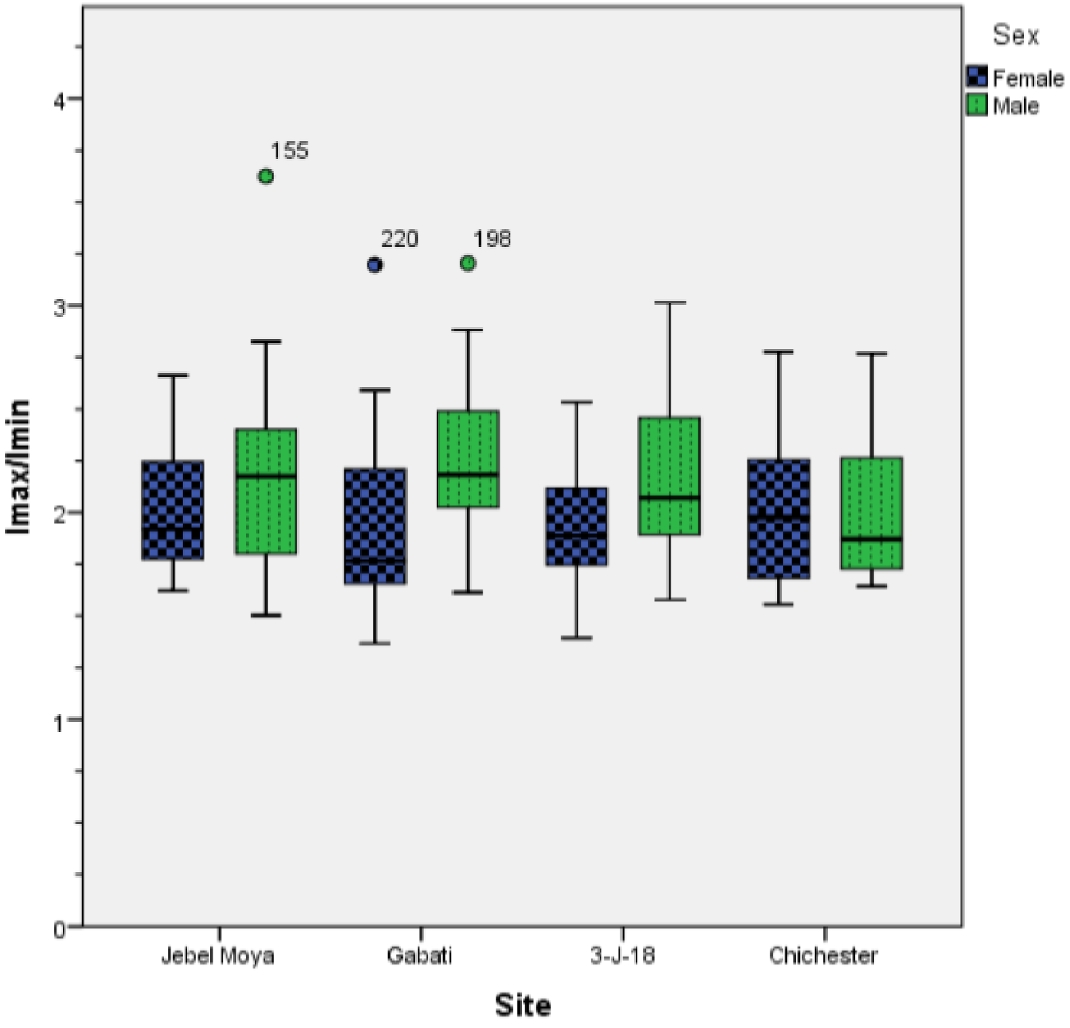


Figure 8.2.16 Boxplot showing I_{max}/I_{min} for males and females by site.

An ANOVA was conducted to examine differences between shape categories based on I_{max}/I_{min}, combining males and females, the results of which are shown in Table 8.2.17 (F(5,242)=25.43, $p<0.001$). A Levene's test of homogeneity of variance was conducted, showing that the results are homogeneous ($p<0.001$). The differences between the triangular and droplet categories are not significant, but the differences between those categories and the other "more altered" shape categories are significant. The differences between I_{max}/I_{min} in the flat side, half-moon, and diamond categories are not significant. A grouping system appears: those that have a posterior buttress, forming a four-pointed shape, and those that do not, forming a three-pointed shape. These groups are more similar to each other in terms of I_{max}/I_{min}.

Shape	Triangular	Droplet	Flat side	Half-moon	Diamond	Ovoid
Triangular		0.803	<0.005		0.012	<0.005
Droplet	0.803		<0.005	0.022	0.001	<0.005
Flat side	<0.005	<0.005		0.364	0.925	<0.005
Half-moon	0.175	0.022	0.364		0.085	0.095
Diamond	0.012	0.001	0.925	0.085		0.095
Ovoid	<0.005	<0.005	<0.005	0.095	0.095	

Table 8.2.17 P-values from the Tukey's post-hoc test for the ANOVA on I_{max}/I_{min} and shape categories.

With regard to other CSG properties and shape, I_{max}/I_{min} shows a slightly different pattern, displayed in Figure 8.2.18. While droplet-shaped tibiae have the lowest mean at 1.82 (±0.2), ovoid-shaped tibiae have the highest mean at 2.68 (±0.38): effectively, the ovoids are the least circular category. A one-way ANOVA with Tukey's post hoc determined the difference between groups was significant (F(5,242)=25.437, p<0.001).

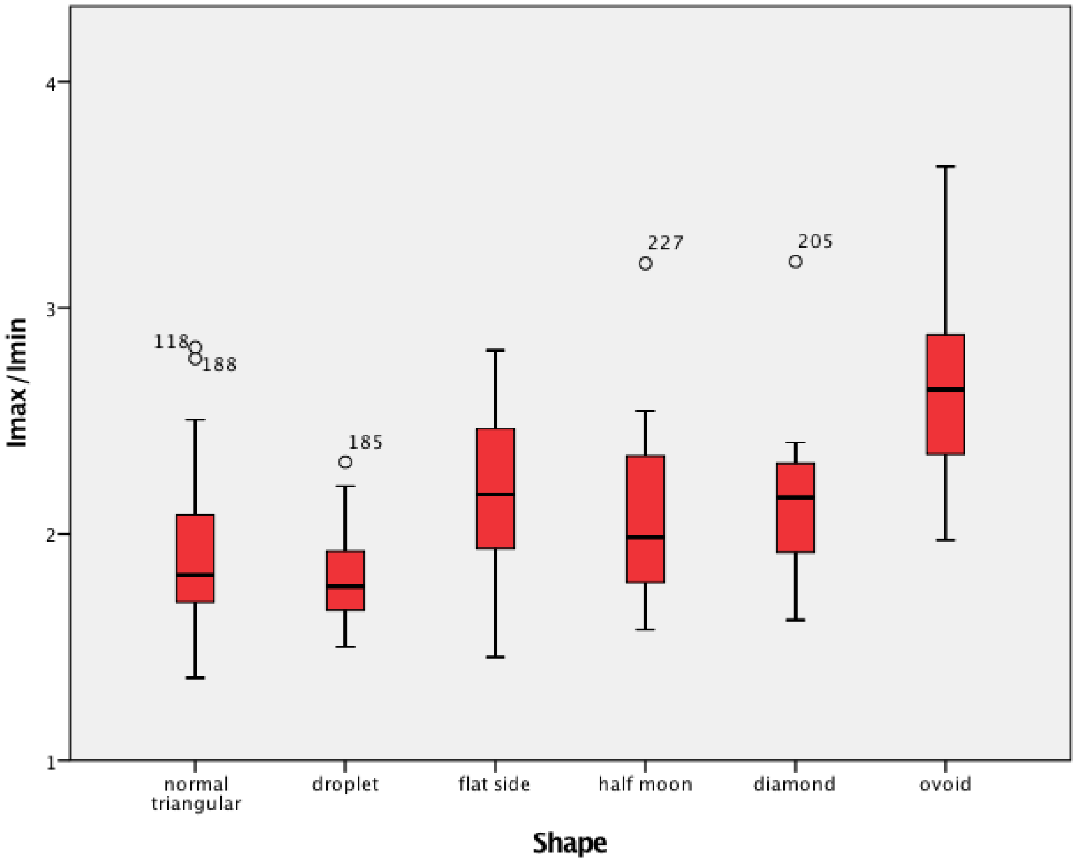


Figure 8.2.18 Boxplot showing shape categories and I_{max}/I_{min} for all individuals.

Summary

I_{max}/I_{min} was similar across all sites. Unlike TA and J, no site stands out; though males have slightly higher I_{max}/I_{min} ratios, females are not that much lower. As I_{max}/I_{min} examines distribution of mass about the maximum and minimum axes and resistance to bending loads, this does not really answer any questions about differences between groups. There does seem to be a pattern in shape distribution, with the three-pointed shapes higher in bending rigidity and the four-pointed shapes lower in bending rigidity, although the difference is not significant. Since those closest to 1 are the most circular, the Gabati and 3-J-18 females are the most circular at 1.25: these are more likely to be droplet-shaped.

8.2.5 Second moment of area in the anteroposterior and mediolateral planes (I_x/I_y)

I_x/I_y compares the same value as I_{max}/I_{min}, but it uses the anteroposterior and mediolateral plane as defined by post-scan orientation. While each scan was orientated using the same guidelines, the tibial shaft often varies in angle (theta) with regard to the proximal end. Thus much of the variety in I_x/I_y may be explained by this torsion rather than differences in bending stress – or, they represent bending stress of a different kind that may benefit from another type of analysis. However, the results are presented here with this in mind. As it is also a ratio, no standardization is necessary.

A boxplot showing I_x/I_y compared by site is shown in Figure 8.2.19. Unlike I_{max}/I_{min} above, the ranges for each site are much greater, values are not evenly distributed, and there are a number of significant outliers. While females at Jebel Moya occupy a smaller range of values than males, females at 3-J-18 and Chichester have a broader distribution and a wider range than the males.

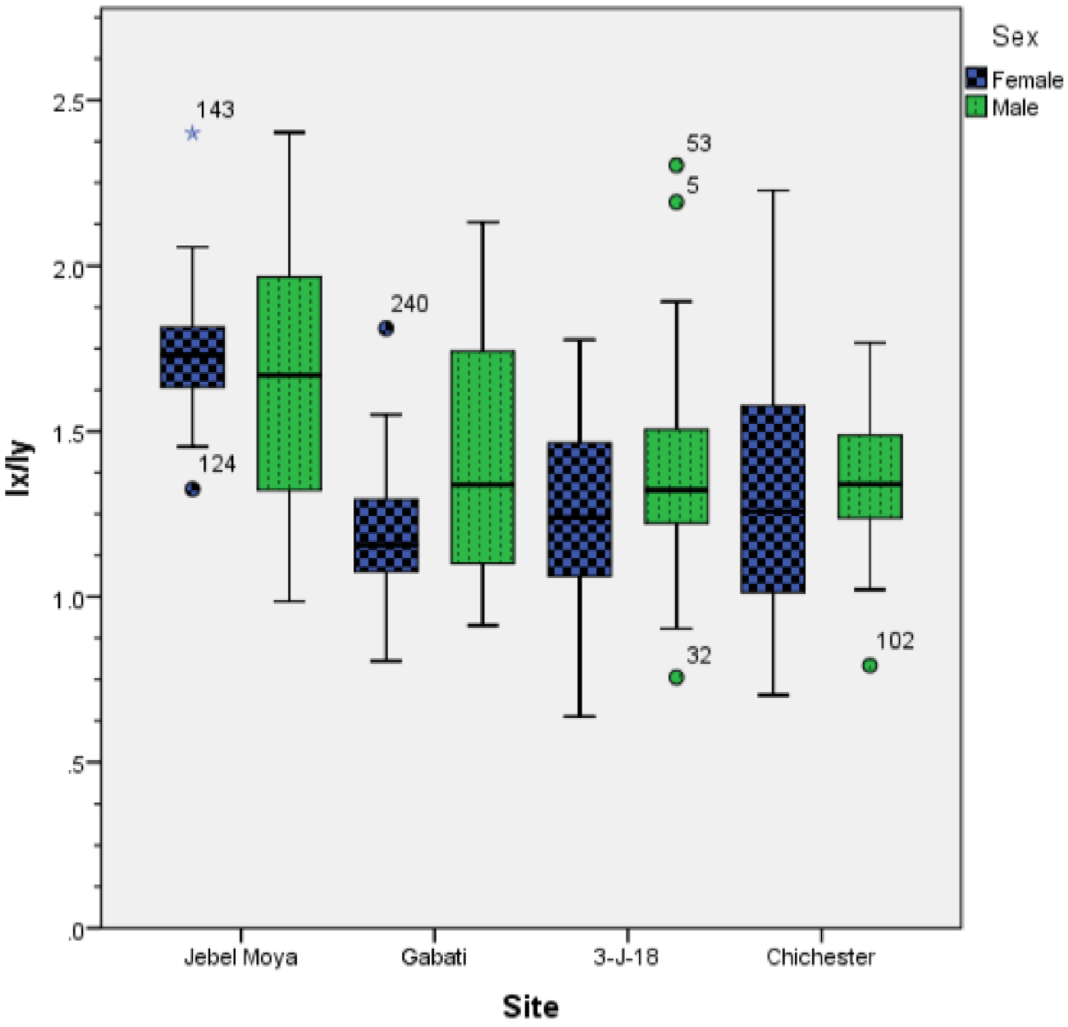


Figure 8.2.19 Boxplot showing I_x/I_y for males and females by site.

An ANOVA was conducted to examine differences between shape categories based on I_x/I_y, combining males and females, the results of which are shown in Table 8.2.20 (F(5.242)=5.09, p<0.001). A Levene's test of homogeneity of variance was conducted, showing that the results are not homogeneous, but there are still some significant differences. Due to the uneven sizes of the groups, a Hochberg GT2 post-hoc test was used and shows a non-significant difference (p=0.06). There are not as many significant differences between the categories as seen in I_{max}/I_{min}: in fact, the only significant differences are seen between the diamond category and all the others.

Shape	Triangular	Droplet	Flat side	Half-moon	Diamond	Ovoid
Triangular		0.994	0.071	0.958	0.001	0.965
Droplet	0.994		0.045	0.829	0.001	0.863
Flat side	0.071	0.045		0.825	0.344	0.927
Half-moon	0.958	0.829	0.825		0.076	1
Diamond	0.001	0.001	0.344	0.076		0.177
Ovoid	0.965	0.863	0.927	1	0.177	

Table 8.2.20 P-values from Welch's post-hoc for the the ANOVA on I_x/I_y.

With regard to CSG properties and shape, I_x/I_y showed less variation between categories, although a one-way ANOVA with Tukey's post hoc still determined the difference between groups was significant (F(5,242)=5.098, p<0.001). The lowest mean, predictably, was that of the droplet-shaped tibiae at 1.29 (±0.31) and the highest was diamond at 1.66 (±0.35). This is shown in Figure 8.2.21.

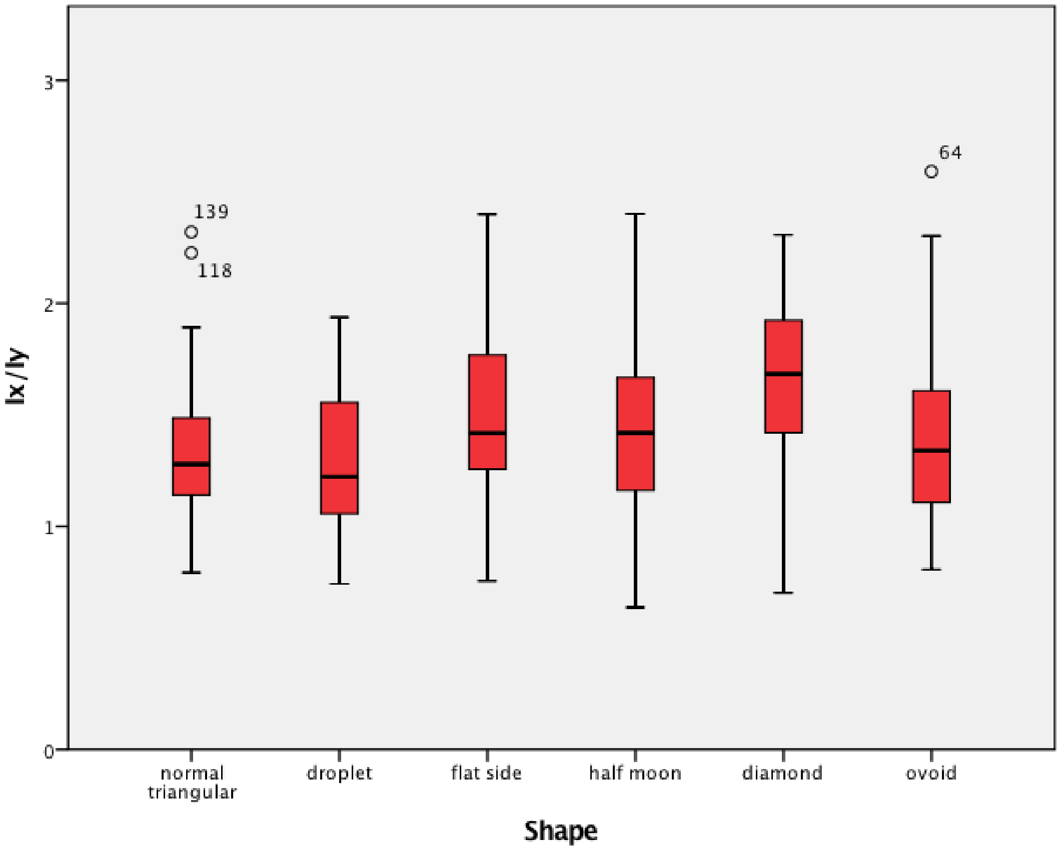


Figure 8.2.21 Boxplot showing shape categories and I_x/I_y for all individuals.

A nonparametric Wilcoxon signed rank test was conducted to compare I_{max}/I_{min} and I_x/I_y; the difference was found to be significant ($p<0.001$, $Z=-13.761$). (This was used to align with other researchers' results despite the normal distribution in this sample.) Figure 8.2.22 shows the two second moments of area plotted against each other. A Pearson product-moment correlation was run to determine the relationship between these two values. There was a significant positive correlation ($r=0.319$, $n=252$, $p=0.001$).

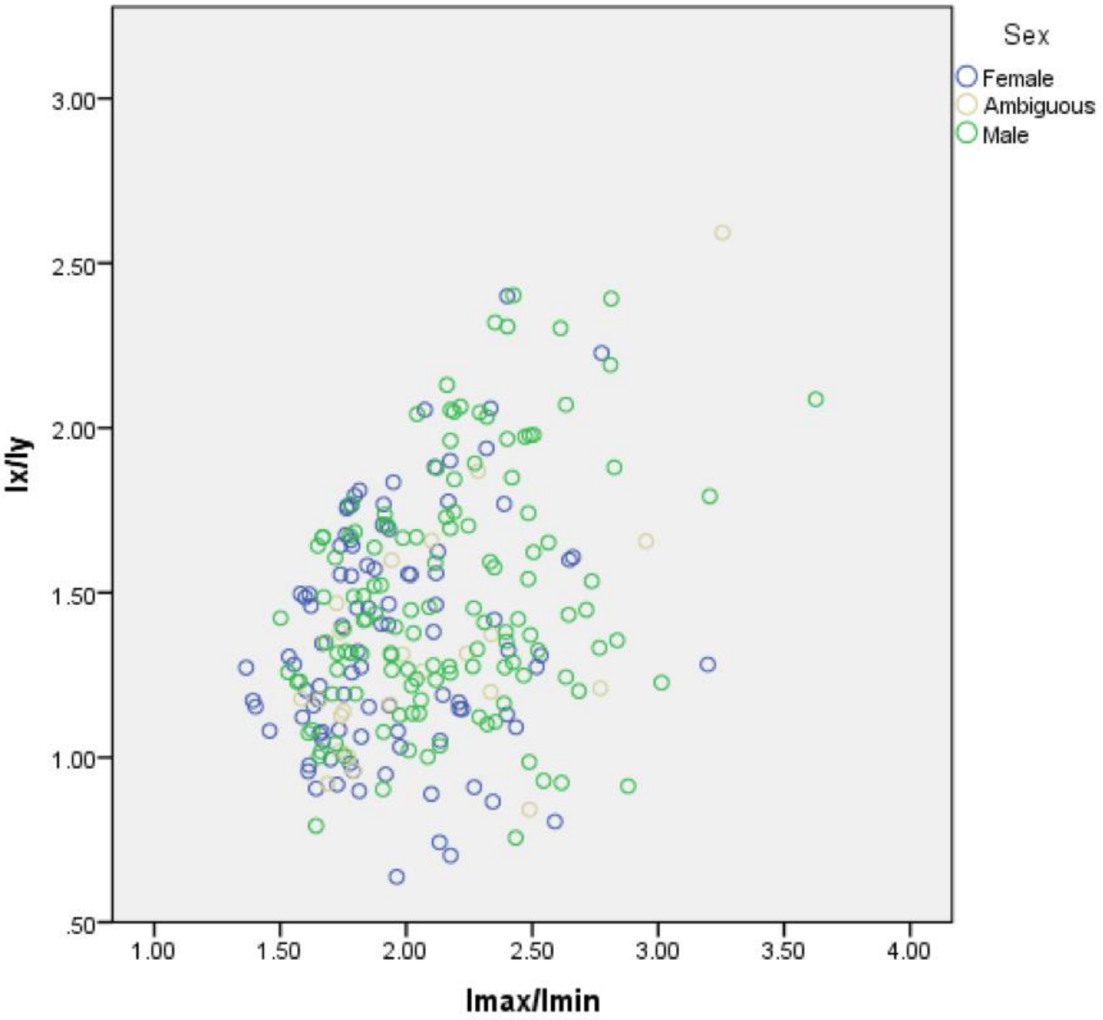


Figure 8.2.22 Two second moments of area plotted against each other for all individuals.

Theta

The angle of rotation (θ) was measured in order to test a correlation between I_x/I_y and lateral rotation. The minimum angle is 23.73° and the maximum 89.22° with a mean of 60.51°; the ranges at each site for each sex are shown in Table 8.2.24. Using an ANOVA, the difference between theta at each site was found to be significant for females (F(3,89)=14.043, $p<0.001$) and for males (F(3,121)=5.273, p=0.002). The females tend to have lower theta minima, but the female theta maxima were almost equivalent to the males and in some cases higher.

	Minimum	Maximum	Mean	SD	N
Jebel Moya	44.59	89.22	69.16	11.86	67
Males	44.59	89.22	66.93	11.88	45
Females	30.84	88.77	57.97	11.81	42
3-J-18	23.73	76.22	56.57	10.61	84
Males	35.36	76.22	57.42	10.35	40
Females	23.3	76.05	55.85	11.16	35
Gabati	40.72	87.71	57.64	11.99	49
Males	42.36	84.76	61.06	12.6	23
Females	40.72	87.71	54.89	11.6	21
Chichester	30.84	57.97	57.97	11.81	42
Males	30.84	88.77	59.16	13.25	18
Females	39.75	75.95	58.33	12.56	15
Overall	23.73	89.22	60.51	12.6	242

Table 8.2.24 Theta minimum, maximum, mean, standard deviation, and number of individuals tested divided by site and sex.

A linear regression was run to test whether I_x/I_y would predict theta (R=0.823, $r^2=0.678$). The beta coefficient was significant ($p<0.005$, $I_x/I_y = .823\theta + 20.313$). A Pearson product-moment coefficient correlation was also run to determine the relationship between I_x/I_y and theta. There was a significant positive correlation (r=0.823, n=241, p=0.001).

Summary

The results for I_x/I_y are not as simple to interpret as those for I_{max}/I_{min}. There is a wide range of results, with many spanning 1 (most circular) and some even going below. Chichester females and Jebel Moya males covered the widest ranges, and Jebel Moya females the smallest. There are also quite a few outliers. The ANOVA also revealed a significant difference not seen in any of the other results. Analysis of theta showed that while I_x/I_y may be able to predict the difference in angle, there is still significant variation. Despite their correlation with theta, due to the differences between I_x/I_y and the other results and its dependence on an alignment within the scanner rather than an anatomical feature, it may be worthwhile to discount these results.

8.2.6 Comparison to other sites

It is useful to compare TA, J, I_{max}/I_{min}, and I_x/I_y to the results of published studies, where possible. Many of the early human and Neanderthal results are analyses of only one individual and often only one bone, while modern studies present the mean of all individuals in the study. Some are presented standardised and other unstandardized, and some are solid sections and some exclude the medullary cavity. All values vary greatly, indicating the need for more data collection and sharing. Note that not all individuals with the highest TA and J values have high I_{max}/I_{min}, which was also found in this study (Chapter 8.2.4). The values included in other publications are too diverse to make accurate comparisons with the study data so are presented here for reference.

	TA	J	*Imax/Imin*	*Ix/Iy*
Trinkaus & Ruff 2012				
KNM-ER 813b	458	34023	1.977	1.844
Broken Hill E691	602	62127	2.21	2.02
Boxgrove 1	**766**	**99737**	**2.03**	**1.94**
Ngandong 13	712	81601	2.05	1.86
Ngandong 14	445	33558	2.18	1.86
Amud 1	603	64152	2.77	2.62
Ferassie 1	611	65943	3.08	3.087
Ferrassie 2	439	29232	1.94	1.52
Qafzeh 8	644	65702	1.71	1.71
Skhul 5	741	86569	2.24	2.24
Skhul 6	566	54764	2.35	2.04
Cro-Magnon 4330	609	67096	2.46	2.18
Cro-Magnon 4333	550	51940	1.72	2.32

Dolni Vestonice 14	445	35347	3.85	2.7
Dolni Vestonice 16	507	43000	2.32	1.73
Ohalo 2	503	46079	3.04	2.28
Paviland 1	549	55791	3.62	2.75
Veneri 1	625	76500	3.5	3.27
Veneri 2	563	53600	1.91	1.91
Shaw & Stock 2009				
Hockey Player*	*506.41*	*465.4*	*2.22*	
Runner*	*532.11*	*501.34*	*2.604*	
Control*	*481.83*	*381.04*	*2.283*	
Ledger *et al.* 2000				
Modern male*	***794***		**2.2**	**1.31**
18th c. male*	***817***		**2.5**	**1.25**
Hunter-gatherer male*	***847***		**2.7**	**1.89**
Modern female*	***873***		**2**	**1.36**
18th c. female*	***852***		**2.3**	**1.07**
Hunter-gather female*	***778***		**2.4**	**1.87**
Ruff 1983				
Pecos Pueblo	396.6	25784	2.93	
Modern US (Miller & Purkey)			2.09	
Modern Japanese			2.18	
Modern US (Minns)			2.12	
Modern (Piziali et al.)			2.4	
Jebel Moya	*513.6*	*47981*	*2.1*	*1.66*
3-J-18	*377.3*	*25666*	*2.06*	*1.33*
Gabati	*353.4*	*23176*	*2.08*	*1.31*
Chichester	*411.65*	*31160*	*1.99*	*1.32*

Table 8.2.26 Cross-sectional geometric properties compared between this study and previously published research. *Italics* indicate means of the sample rather than individual values, asterisk* indicates standardisation for body mass, and **bold** indicates solid section, although sometimes these were not explicit in the text. Studies used are Trinkaus and Ruff (2012), Shaw and Stock (2009), Ledger *et al.* (2000), and Ruff and Hayes (1983).

8.3 Shape analysis

This section displays the results of the geometric morphometric analyses. It is divided into two sections: 8.3.1 displays results obtained through GMM analysis using 6 points using Morphologika v2.5 and subsequent analyses in PAST3, and 8.3.2 displays results obtained through GMM analysis of the entire outline using R. Any difference in results obtained through these methods will be discussed in the next chapter.

8.3.1 Landmarks and semilandmarks

This section displays the results of the analyses using 6 points on the external outline of the tibial midshaft cross-section. 4 points are landmarks, or permanent points on homologous biological features (anterior crest, most posterior point, most medial and most lateral points), and 2 are semilandmarks, or midpoints between these landmarks.

It is possible to sort the individual x- and y-coordinates after Procrustes to see the variation on a Cartesian grid. This is shown in Figure 8.3.1 with 95% ellipses around each of the six landmarks and semilandmarks. It is flipped 90° counterclockwise, with the most anterior point on the tibial crest at the left-hand side. A one-way ANOVA was performed on the Procrustes-adjusted points, showing a significant difference between groups (site and sex, $p<0.001$).

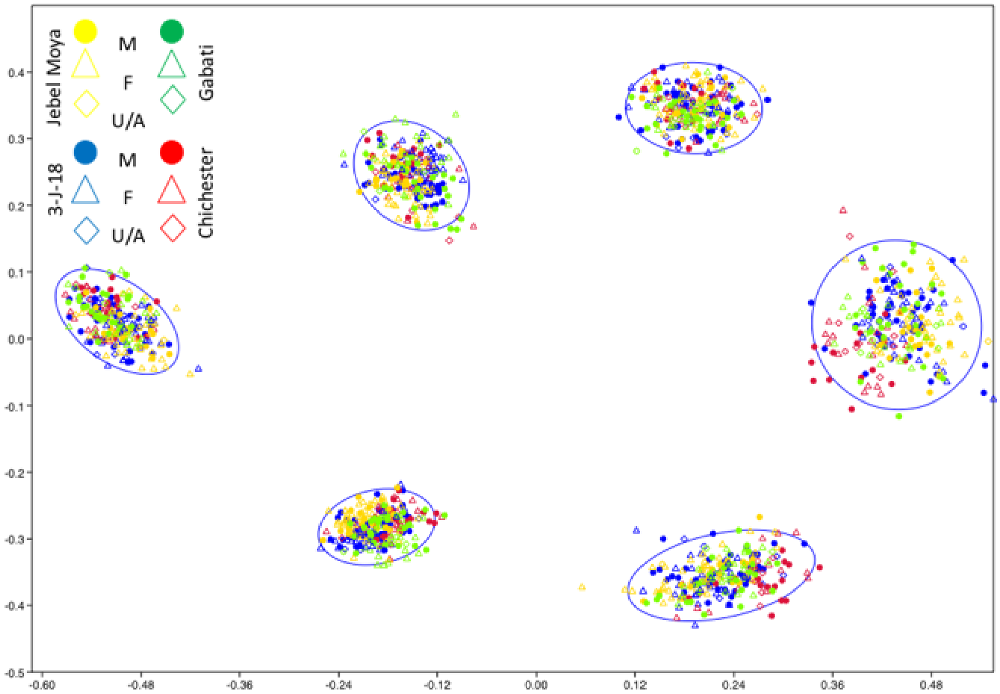


Figure 8.3.1 Each landmark or semilandmark plotted by coordinate. The x and y axes display distance from a centroid in anteroposterior (horizontal axis) and mediolateral (vertical axis) directions.

Principal component analysis was conducted on all individuals with a measurable outline (n=244). These points were subjected to a generalised Procrustes analysis and then PCA. The results of the initial PCA are shown in Figure 8.3.2. There is some grouping by site, although there appear to be many outliers.

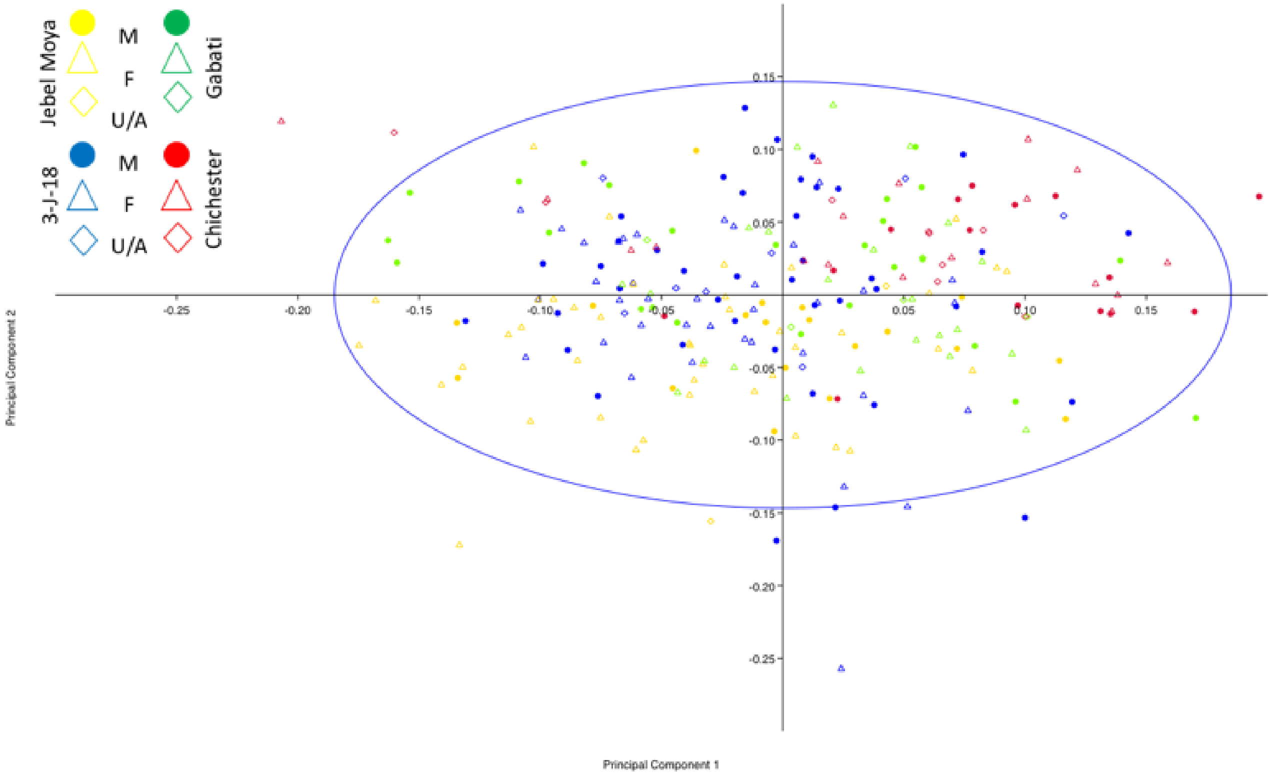


Figure 8.3.2 Principal component analysis by site and sex with a 95% ellipse. The x-axis is PC1 and the y-axis is PC2. Jebel Moya is yellow, 3-J-18 is blue, Gabati is green, and Chichester is red. Females are represented by circles, males by triangles, and ambiguous/unassigned by diamonds.

Exploring shape space within Morphologika allows for computation of the average tibia based on the 6 landmarks, which is most similar to the diamond shape category. This also enables visual examination of the principal components. PC1, the x-axis, appears to be the location of the most medial point: on the far right, it is very close to the most posterior point, and on the far left, it is much further towards anterior. PC2, the y-axis, appears to be the length of the lateral edge from anterior to the interosseous crest. At the top, it is short and extends outwards; at the bottom, it is long and creates a shape similar to the flat side category, shown in Figure 8.3.3. Principal component 1 accounts for 39.063% of variance and principal component 2 accounts for 24.593% of variance (together they account for 63.656% of variance). Principal component 3 accounts for an additional 13.108%, bringing the total for the first three principal components to 76.764%. PC3, plotted against PC1 in Figure 8.3.4, appears to be the angle of the lateral sulcus. Principal component 4 accounts for 8.053%, principal component 5 for 5.248%, principal component 6 for 3.958%, and principal component 6 for 3.223%; the first 6 components account for 97.246% of variation. This is shown in the scree plot, which displays the percentage each principal component accounts for in descending order, in Figure 8.3.5, with eigenvalues. The last three principal components can be ignored, as there are always three more principal components listed than exist due to the calculations used.

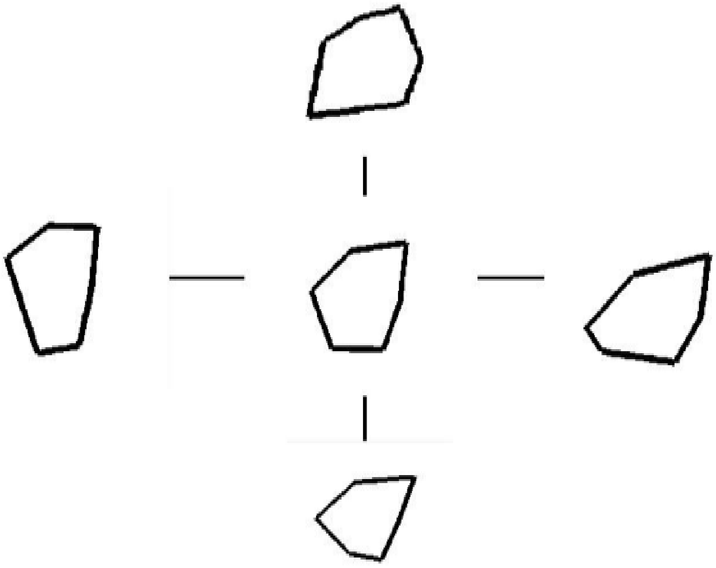


Figure 8.3.3 The mean shape and extreme shapes at opposite ends of principal components 1 (x-axis) and 2 (y-axis).

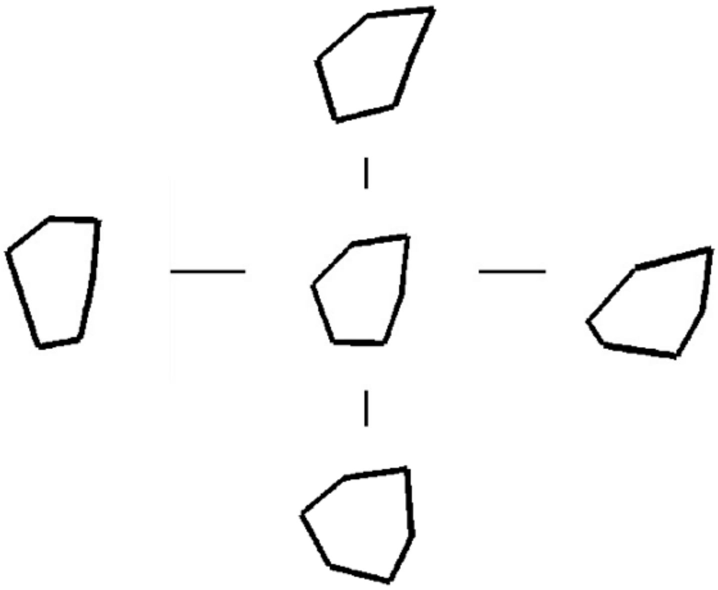


Figure 8.3.4 The mean shape and extreme shapes at opposite ends of principal components 1 (x-axis) and 3 (y-axis).

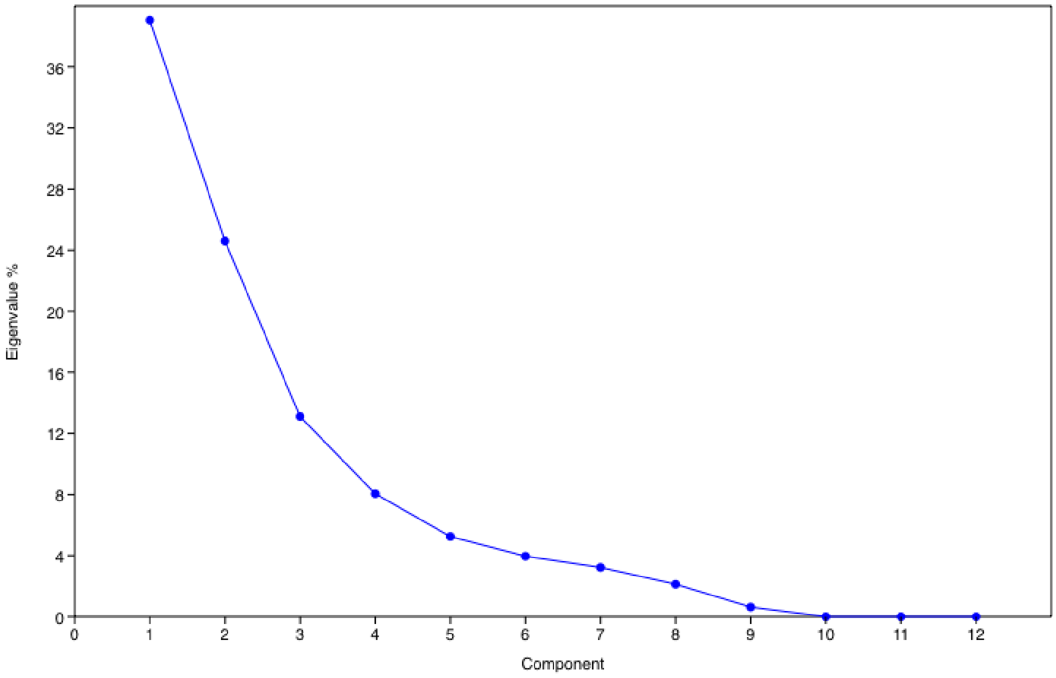


Figure 8.3.5 Scree plot of principal components vs eigenvalues.

8.3.2 Outline

This section displays the results of the analyses using the entire external outline of the tibial midshaft cross-section. For this, the R program was utilised with the packages Momocs (Bonhomme *et al.* 2014) and Geomorph (Adams and Otárola-Castillo 2013; Adams *et al.* 2015). 238 tibial cross-sectional images were analyzed after an initial change from white-on-black to black-on-white images. The images were centered and overlayed, shown in Figure 8.3.6; a Procrustes was applied automatically following this command.

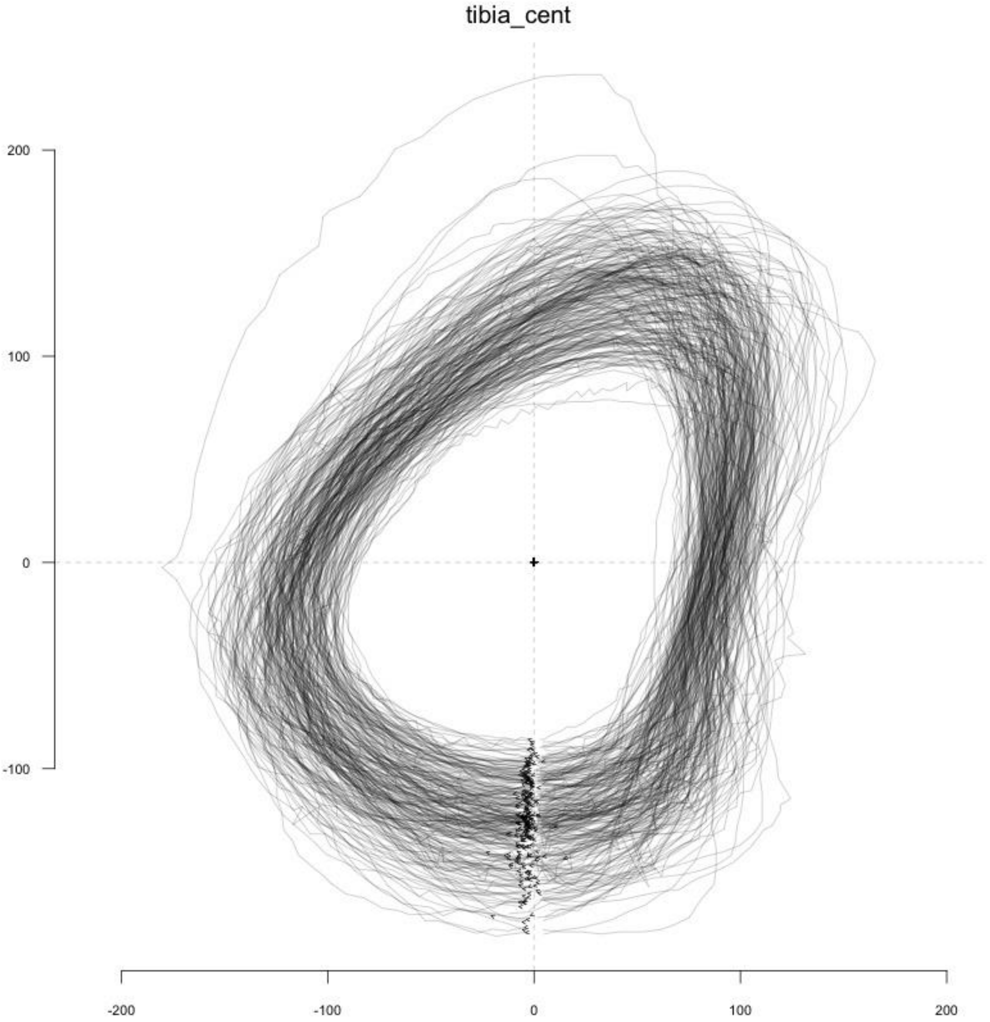


Figure 8.3.6 All tibial outlines centered and overlaid after Procrustes, showing differences in outline shape. The wiggles are an artifact of the scanning process and are eliminated in the next stage of analysis when shapes are smoothed.

An elliptical Fourier analysis showed that nine harmonics accounted for all the variation, so further analysis used nine harmonics rather than more, shown in Figure 8.3.7. This should give more accurate results than the landmarks used above, as more factors are involved and human error is removed.

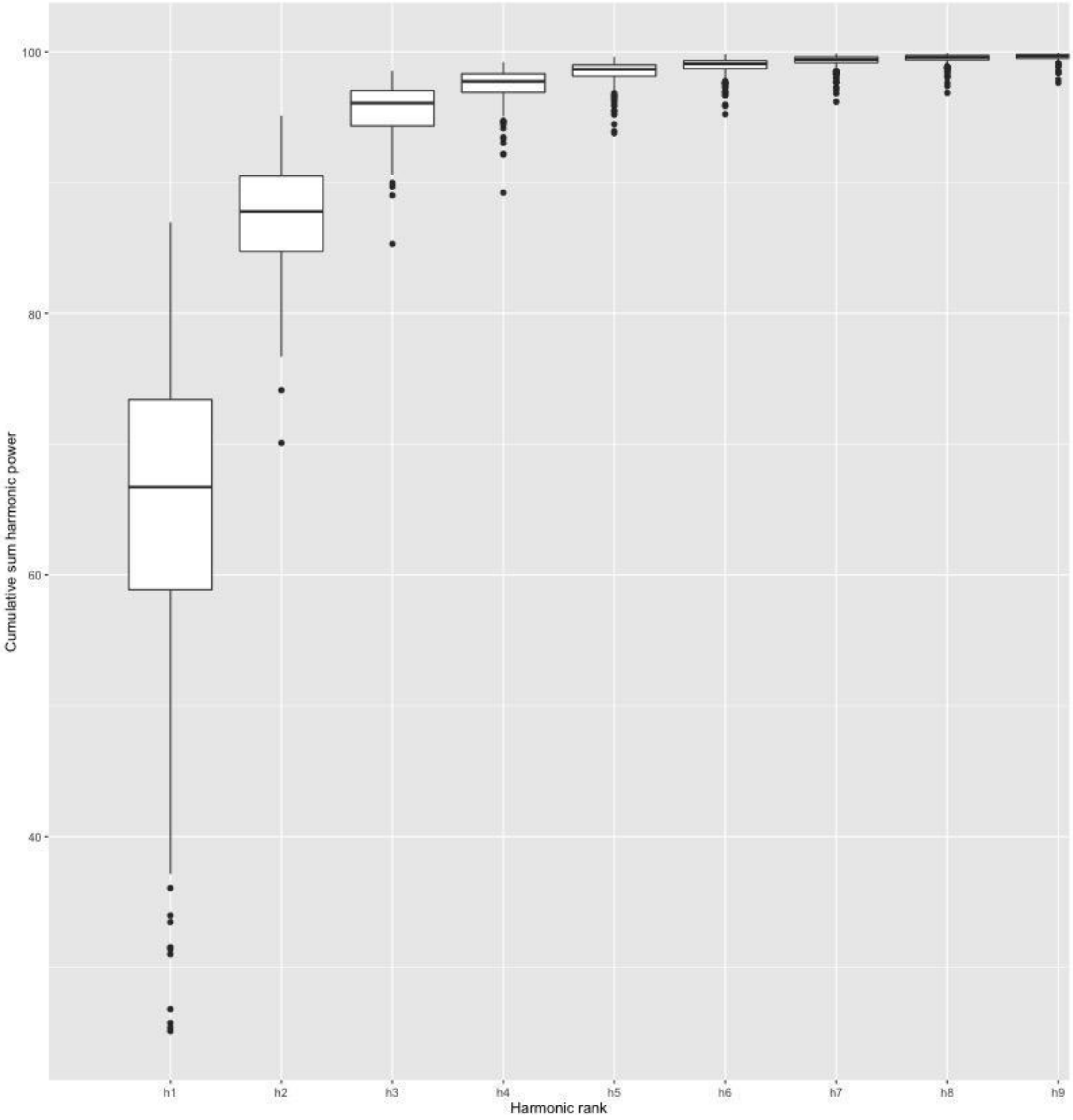


Figure 8.3.7 Harmonic rank of tibial shape showed nine harmonics.

Overall principal component analysis

A principal component analysis was performed, the results of which are shown in the figures below. Figure 8.3.8 shows the results of principal component analysis comparing principal component 1 against principal component 2, with sample shapes from each quadrant. Note that in R, the tibial cross-sections are not rotated: the landmark of the anterior crest is facing to the top of the coordinate plane. Principal component 1 accounts for 48.4% of the variation, and principal component 2 accounts for an additional 22.9% (total 72.3%), represented as eigenvalues in the bottom right corner of the plane. Examining the shape variation, principal component 1 appears to be the shape of the medial side of the tibia between the most medial point and the anterior crest – towards the positive end, it is short and towards the negative end it increases in length. In a shape amplification chart (not shown), it becomes clear that a medial sulcus appears towards the negative end. Principal component 2 appears to be the width of the anterior end: it is rounded at the positive end of the y-axis and pointed at the negative end. The shape outline closest to the centre would be classified as triangular. Four shape categories can be seen on the plane – triangular closest to the centre, droplet above it and to the right, flat side at (x,y), and half-moon at (x,-y). Note that while the plane shows some tibial shapes that do not exist in this study (-x,-y), there are no individual points on those shapes so they can be considered the principal components carried to an extreme. Note that they are only examples of possible shapes in that quadrant and do not correspond directly to any data points placed over them – they are also spaced for ease of viewing, otherwise they would be too large or too small for display in this chapter. For calculated mean shapes for each site, see the Appendix.

The following charts show a scatter plot of individuals, sometimes divided into categories, based on the principal components examined. This is overlaid onto images showing calculated distortions of each shape up to three standard deviations from the mean. The location of individuals on the scatter plot does not directly correlate to the shape images; they are merely illustrative of the variation that can occur. In some instances, the scatter plot groupings show a tilted axis. This indicates that if only that group were examined, the axis of variance would be shifted and change the standard deviation shapes.

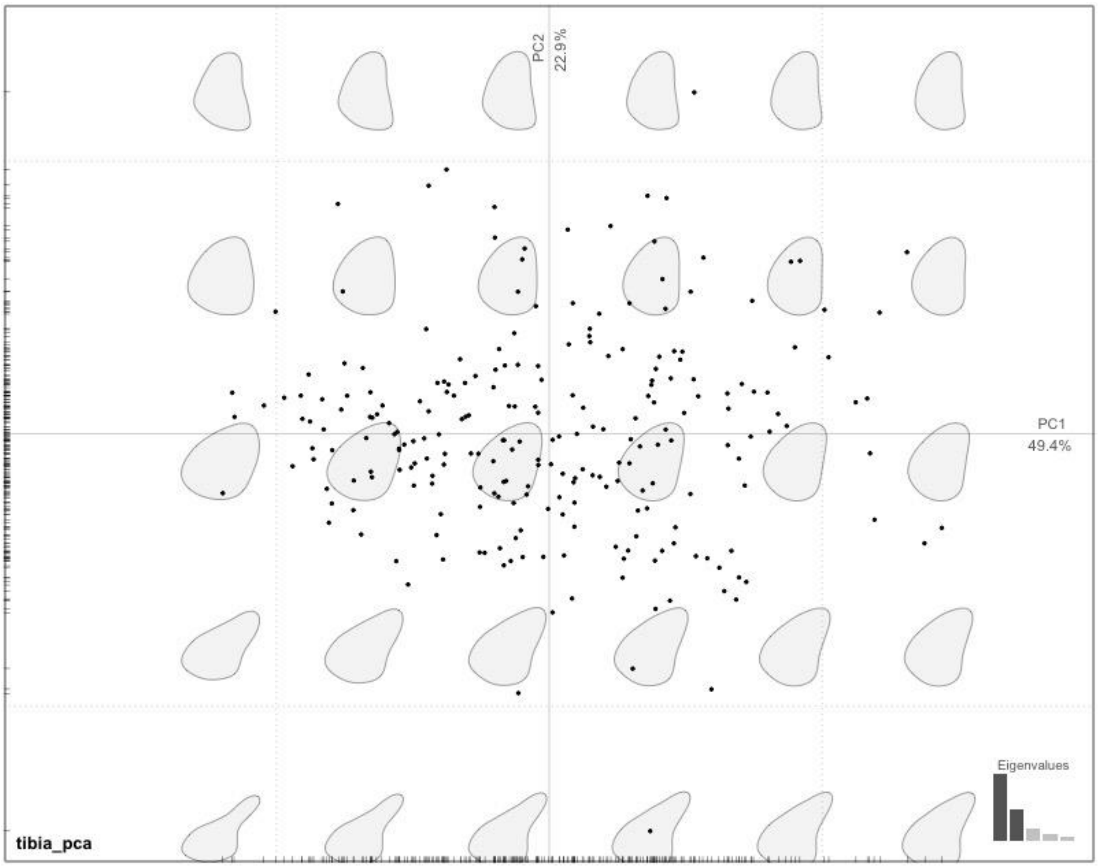


Figure 8.3.8 The principal component analysis of PC1 (horizontal axis) plotted against PC2 (vertical axis) for all individuals examined displayed as a coordinate plane.

Figure 8.3.9 shows principal components 1 and 3. Later figures show principal components 1 vs 2 and 2 vs 3, but this figure is provided to illustrate exactly what differentiates principal component 3 from the others. Principal component 3, which accounts for 9.11% of variation (total 81.41%), appears to be three-pointedness vs four-pointedness, with more triangular shapes towards the negative end of the y-axis and more diamond-like shapes towards the positive end. Note the individual data points in the (x,y) quadrant, which seem to be the diamond/half-moon shapes.

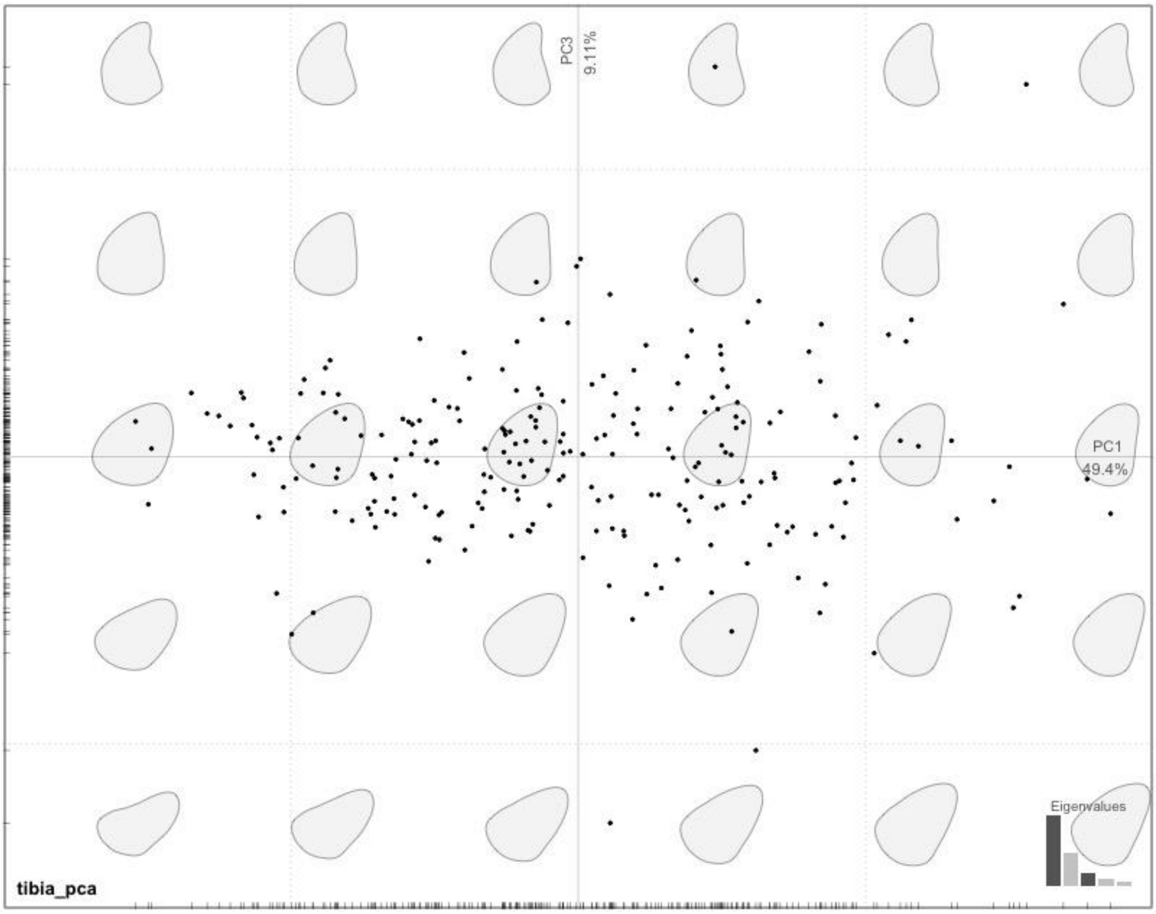


Figure 8.3.9 The principal component analysis of PC1 (horizontal axis) plotted against PC3 (vertical axis) for all individuals examined displayed as a coordinate plane.

Comparison by sex

A comparison of principal component 1 and principal component 2 with an added layer of sex is shown in Figure 8.3.10. The axes for each sex are slightly rotated, indicating a slight difference in the alignment of that principal component. As discussed above, principal component 1 appears to be either the depth of the interosseous sulcus or the protrusion of the medial edge, while principal component 2 appears to be mediolateral width at the anterior edge. Note that principal component 1 remains the same width along the x-axis while principal component 2 is wider at the positive end and narrower at the negative end of the y-axis. The central cross in each ellipse indicates a slight variation of the x- and y-axes for the group examined. The ellipses indicate 95% confidence interval. The outliers might be individuals for whom sex assessment was incorrect, or the few robust (or diamond-shaped) females or gracile (or triangular/droplet-shaped) males.

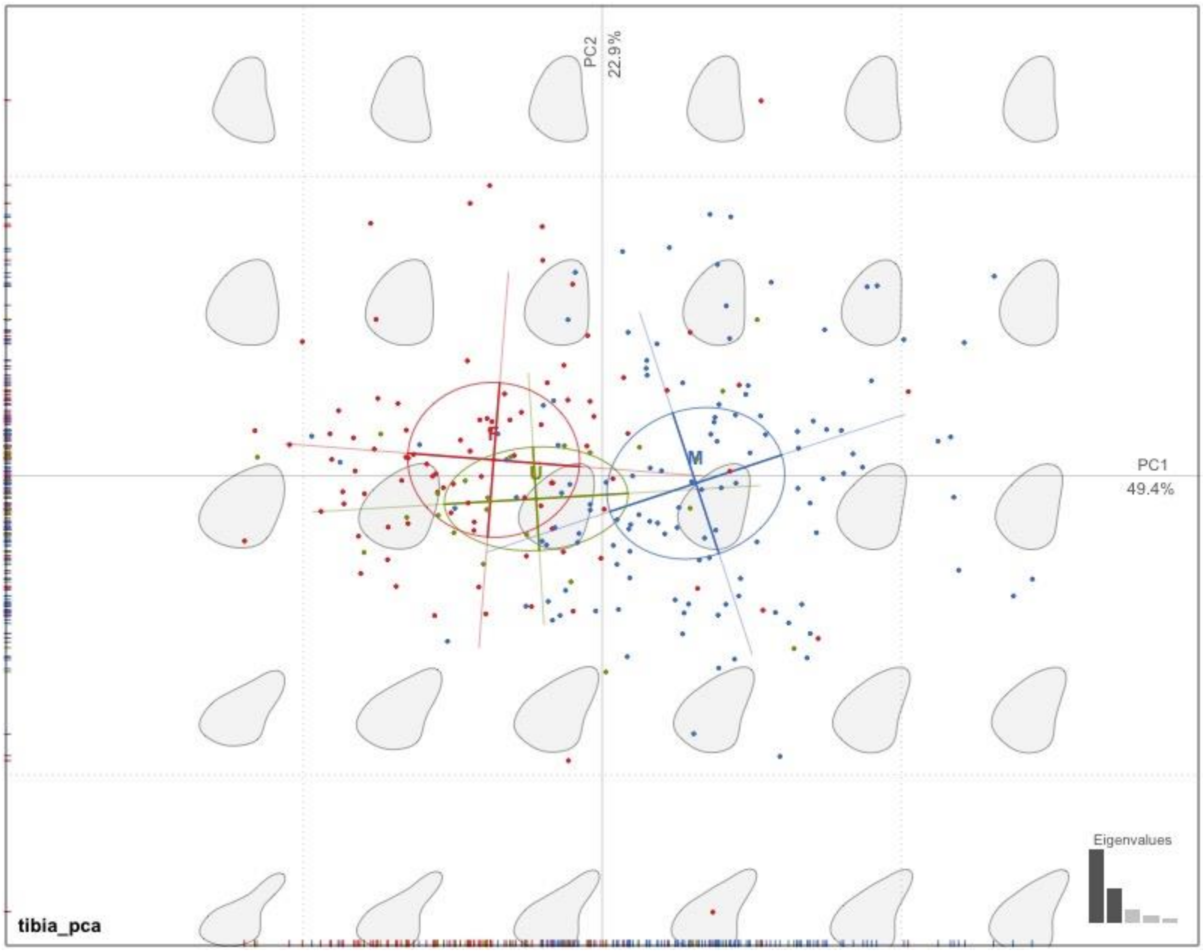


Figure 8.3.10 PC1 (horizontal axis) plotted against PC2 for all individuals in a coordinate plane overlaid by sex: F=female, U=ambiguous/unassigned, M=male, with 95% ellipses.

Principal components 2 and 3 were compared by sex as well, shown in Figure 8.3.11.

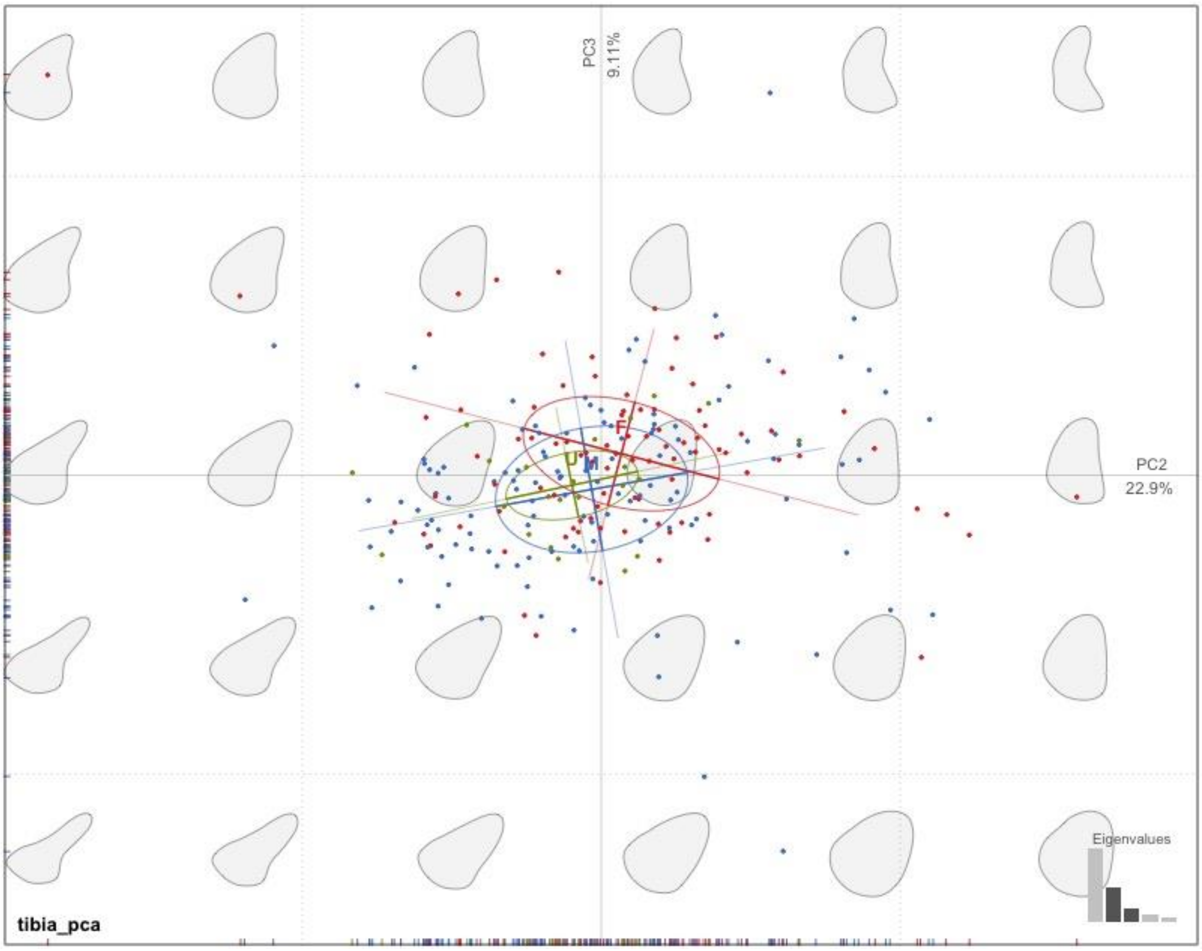


Figure 8.3.11 PC2 (horizontal axis) plotted against PC3 for all individuals in a coordinate plane overlaid by sex: F=female, U=ambiguous/unassigned, M=male, with 95% ellipses.

A MANOVA was conducted to test the significance of sex categories, the p-values of which are shown in Figure 8.3.12. Significant differences are seen between all three categories, the strongest of which was between females and males (F(1,235)=2.118, p<0.001). Slightly less significant was the difference between males and unassigned/ambiguous (F(1,235)=6.3008, p=0.011), while the difference between females and unassigned are not statistically significant (F(1,235)=0.9208, p=0.1), indicating that the unassigned individuals could be female.

	Male	Unassigned	Female
Male		0.01116	<0.001
Unassigned	0.01116		0.544
Female	<0.001	0.544	

Table 8.3.12 P-values of the Tukey's post hoc for a MANOVA conducted on principal components by sex.

Comparison by robusticity

Robusticity of the soleal line is also compared using principal components, shown in Figure 8.3.13. There is a high degree of variability in the repositioning of the x- and y-axes for each level of robusticity (0=not robust to 5=highly robust).

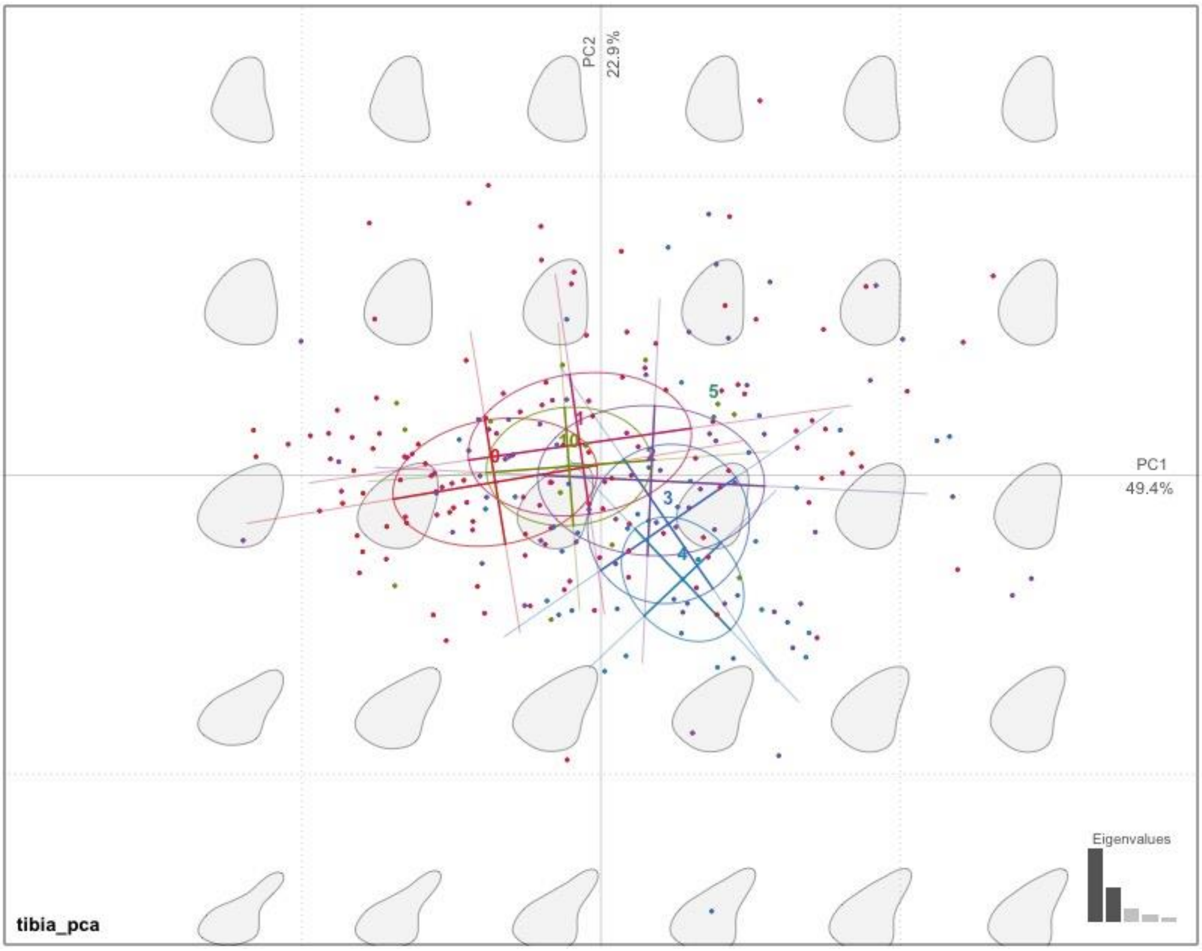


Figure 8.3.13 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all individuals in a coordinate plane overlaid by soleal line robusticity scores: the new axes are labeled 0-5 in order of robusticity as defined by Hawkey and Merbs (1994), with 95% ellipses. 10 is a dummy category.

Robusticity is compared to principal components 2 and 3 in Figure 8.3.14 below. There is not as clear a distinction as that seen in the comparison above, but the lower robusticity categories are closer to (0,0) while the higher categories are further towards positive and negative on the x-axis – when compared to principal component 3, principal component 2 seems to have more of a connection with robusticity scores. Those individuals with a more robust soleal line are towards the more positive end of the x-axis, indicating that those whose first principal component – a deeper lateral sulcus – are more robust.

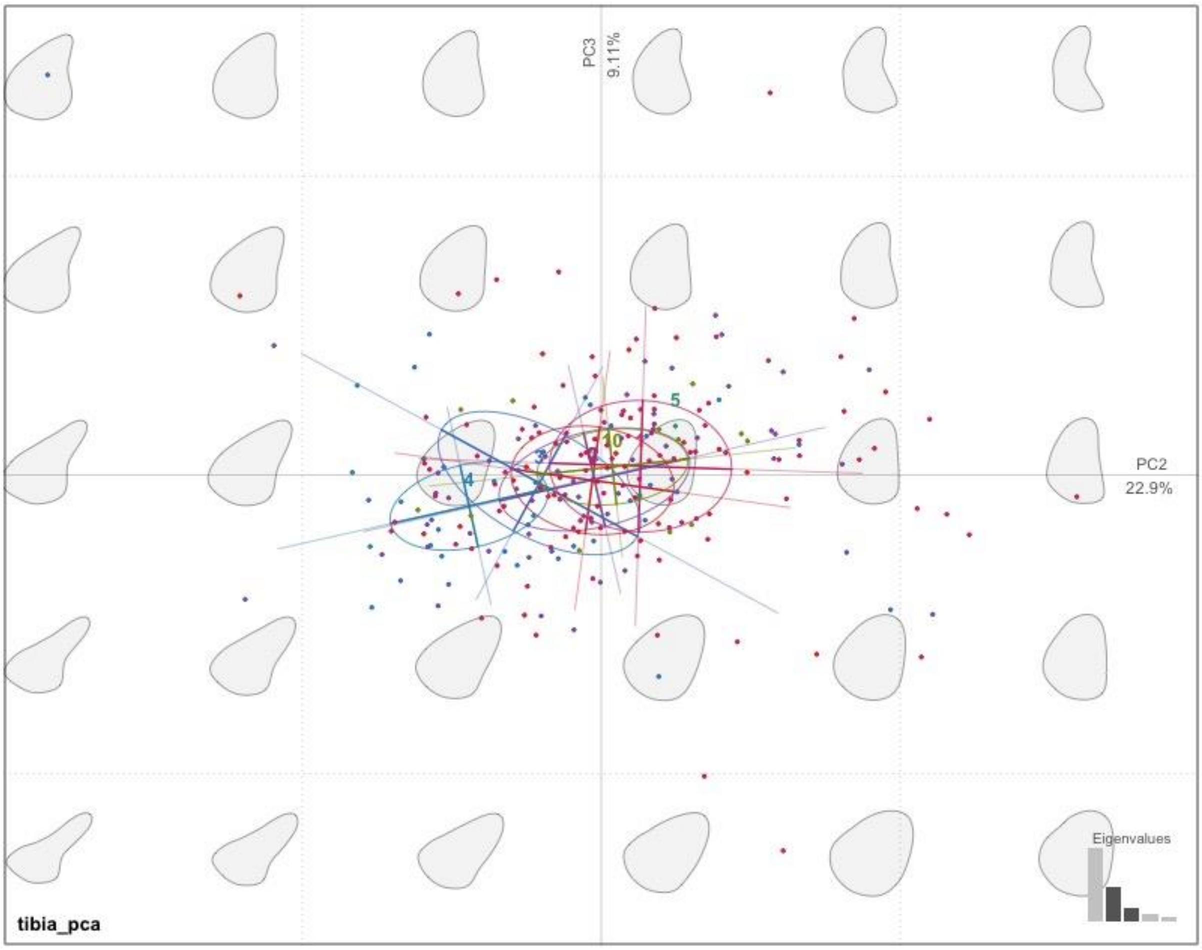


Figure 8.3.14 PC2 (horizontal axis) plotted against PC3 (vertical axis) for all individuals in a coordinate plane overlaid by soleal robusticity: the new axes are labeled 0-5 in order of robusticity as defined by Hawkey and Merbs (1994). 10 is a dummy category.

A MANOVA was performed to assess the significance between groups, shown in Table 8.3.15. The difference between each robusticity level was significant except for levels 3 and 4 (F(5,232)=0.549, p=0.872). Level 0 is significantly different from all other levels. Note that significance increases the further away from the origin – that is, 0 is more significantly different from 4 than it is from 2. This is probably because these are not biological groupings, but exist on a spectrum that is not strictly defined and prone to human error and category conflation.

	0	1	2	3	4
0		0.0062	0.02	<0.001	<0.001
1	0.0062		0.256	0.003	0.006
2	0.02	0.256		0.388	0.694
3	<0.001	0.003	0.388		0.872
4	<0.001	0.006	0.694	0.872	

Table 8.3.15 12 P-values of the Tukey's post hoc for a MANOVA conducted on principal components by robusticity.

Comparison by shape

Shape was also compared using principal component analysis, shown in Figure 8.3.16. The droplet category is quite far from the rest, echoing the results of the CSG analyses above. The diamond category is its opposite, aligned in an opposing ellipse on the opposite side of the y-axis. The other categories are in between the two, centered around the origin. The shape categories do not sit directly on the quadrants in which they're found – possibly because no one quadrant consists entirely of one shape. This will be discussed further in Chapter 9. There is overlap between many of the categories, possibly indicating that they are not as discrete as the inter-observer error tests showed.

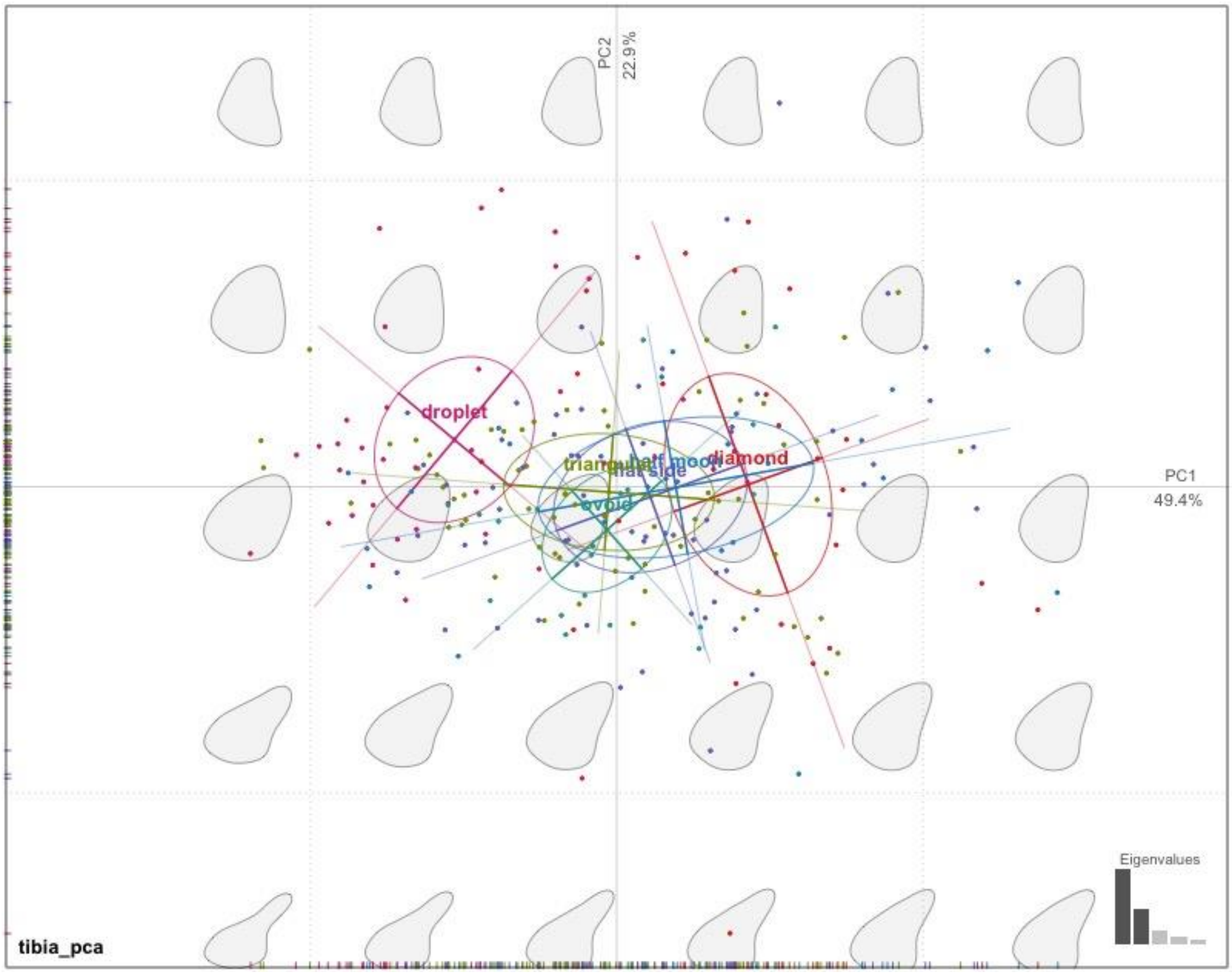


Figure 8.3.16 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all individuals in a coordinate plane overlaid by shape category: triangular, droplet, flat side, half-moon, diamond, and ovoid, with 95% ellipses.

Figure 8.3.17 shows principal component analysis by shape using principal components 2 and 3, with quite a different alignment. In this plane, most shapes cluster around (0,+y), indicating that principal component 3 – number of points - has more of an influence than anterior breadth. Ovoid is pulled towards (-x,-y), which is a similarly elongated and narrow shape.

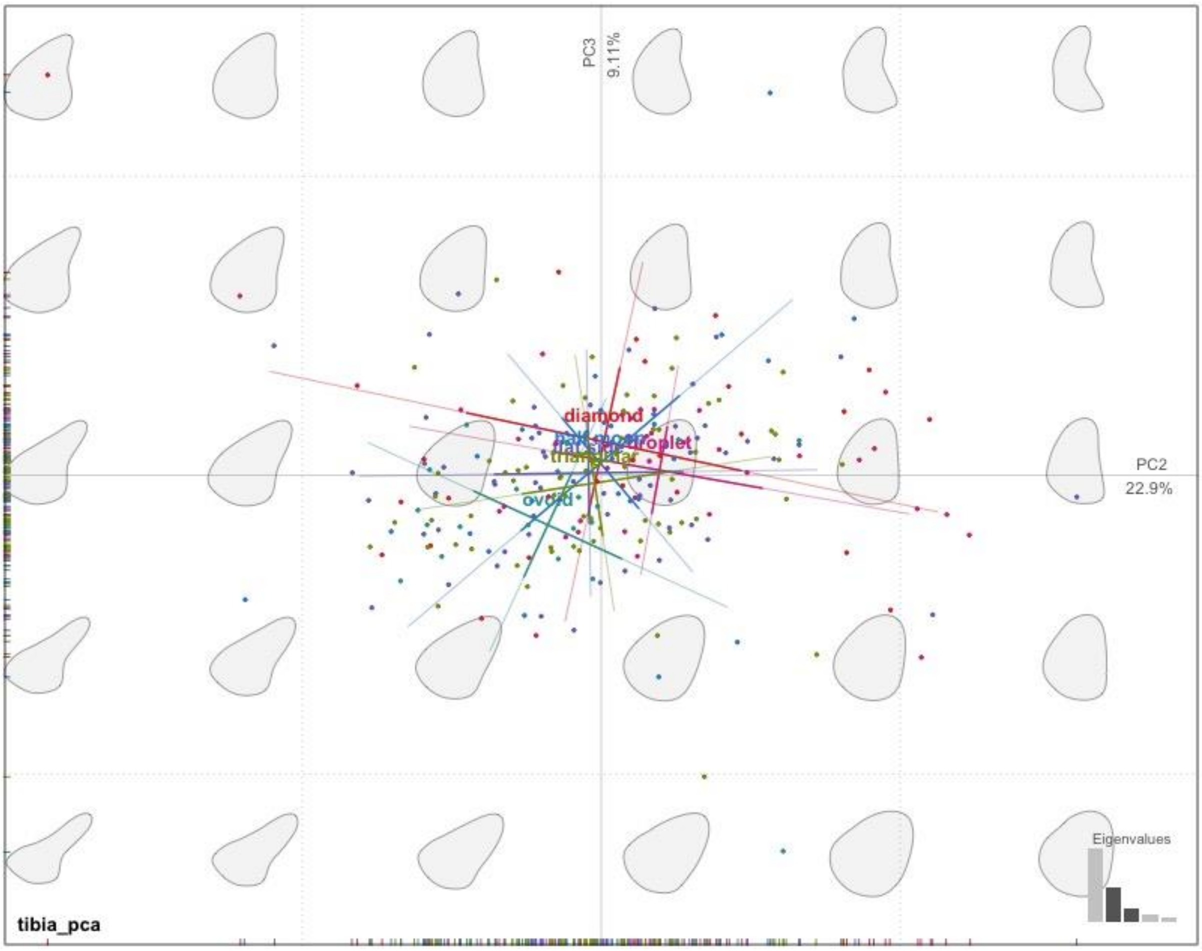


Figure 8.3.17 PC2 (horizontal axis) plotted against PC3 (vertical axis) for all individuals in a coordinate plane overlaid by shape category: triangular, droplet, flat side, half-moon, diamond, and ovoid. 95% ellipses are not shown to avoid cluttering the origin.

A MANOVA was performed to assess the significance between groups, shown in Table 8.3.18 (F(5,232)=4.0009, $p<0.01$). Similar to the statistical analyses in section 8.2, the droplet category was significantly different from the other categories ($p<0.001$ in all cases). All categories are significantly different from each other; the most similar are half-moon, flat side, and diamond, the roughly four-sided categories.

	triangular	droplet	flat side	half-moon	diamond	ovoid
triangular		<0.001	0.0008	0.0231	<0.001	<0.001
droplet	<0.001		<0.001	<0.001	<0.001	<0.001
flat side	0.0008	<0.001		0.0214	0.0016	<0.001
half-moon	0.0231	<0.001	0.0214		0.03369	<0.001
diamond	<0.001	<0.001	0.0016	0.03369		0.001264
ovoid	<0.001	<0.001	<0.001	<0.001	0.001264	

Table 8.3.18 12 P-values of the Tukey's post hoc for a MANOVA conducted on principal components by shape category.

Comparison by site

Site is compared using principal components 1 and 2 in Figure 8.3.19 below. Jebel Moya is distinct from the other three sites, a trend witnessed in CSG analyses above. Its axes are reoriented clockwise by almost 50°, and is pulled towards the positive end of the x-axis. The other three sites cluster around low (-x,-y).

Figure 8.3.19 PC1 (horizontal axis) plotted against PC2 (vertical axis) by site for all individuals in a coordinate plane overlaid by site: JM=Jebel Moya, GB=Gabati, 3J18=3-J-18, and CC=Chichester, with 95% ellipses

Site was also overlaid on the principal components 2 and 3 plane, shown in Figure 8.3.20. Here, Jebel Moya is still separated from the other three sites, although the axis of rotation is not as different as in the last figure.

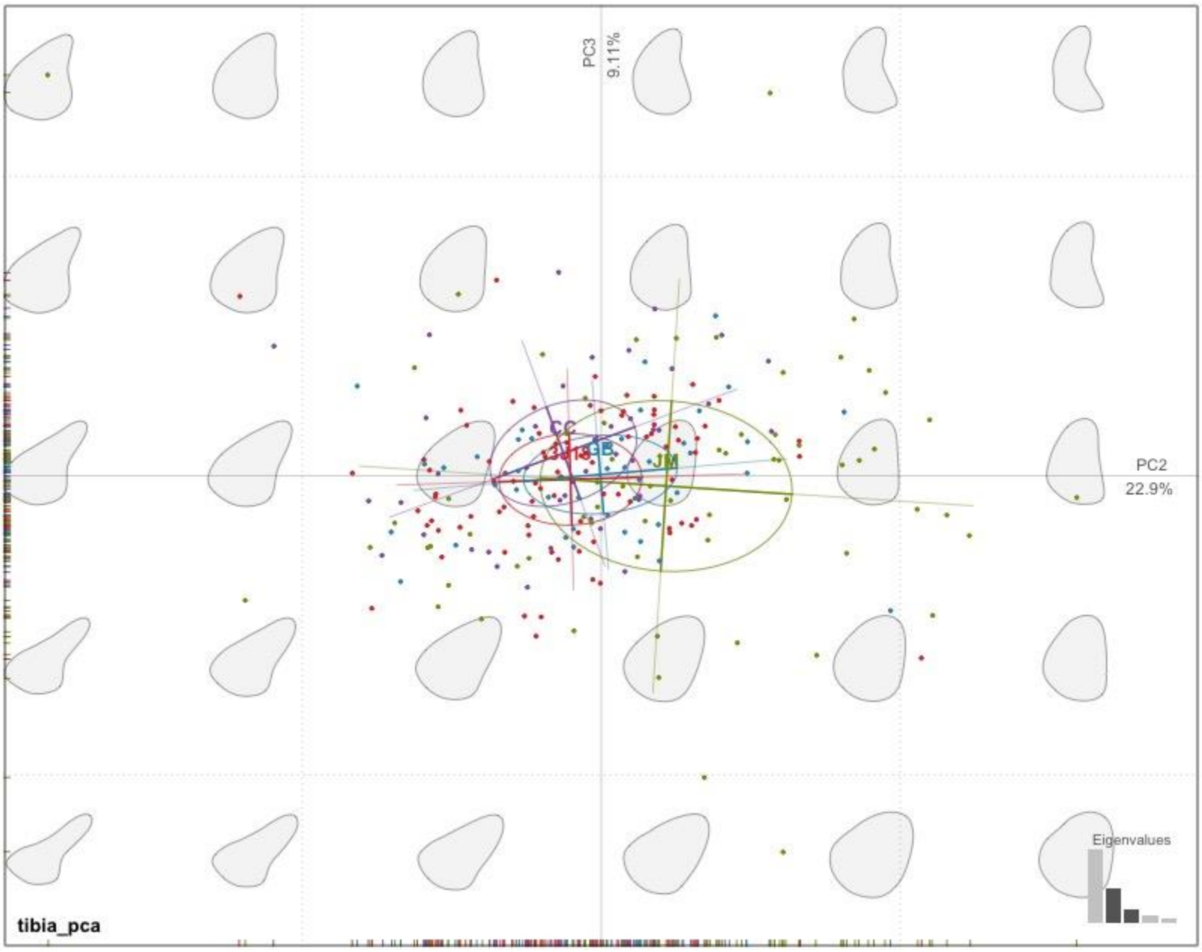


Figure 8.3.20 PC2 (horizontal axis) plotted against PC3 (vertical axis) by site for all individuals in a coordinate plane overlaid by site: JM=Jebel Moya, GB=Gabati, 3J18=3-J-18, and CC=Chichester, with 95% ellipses.

A MANOVA was performed to assess the significance between groups, the results of which are shown in Table 8.3.21 (F(3,238)=7.676, p<0.001). Jebel Moya – as identified in section 8.3 and in the coordinate planes above, is statistically significant from the others (p<0.001) in all cases. The only sites that do not have statistically significant differences with regard to principal components are 3-J-18 and Gabati.

	Jebel Moya	Gabati	3-J-18	Chichester
Jebel Moya		<0.001	<0.001	<0.001
Gabati	<0.001		0.4012	<0.001
3-J-18	<0.001	0.4012		<0.001
Chichester	<0.001	<0.001	<0.001	

Table 8.3.21 12 P-values of the Tukey's post hoc for a MANOVA conducted on principal components by site.

Filters

When filtered by sex, the principal components shift slightly. For instance, principal component analysis performed for only females results in the first principal component accounting for 40.1% of variation instead of 49.4%, and principal component 2 accounts for 32.8% (for a cumulative total of 72.9%). The first two principal components appear to map concordantly onto those established in Figure 8.3.8, but the negative and positive ends of principal component 2 have been flipped. Figure 8.3.22 shows that Jebel Moya is still separated compared to the three agricultural sites.

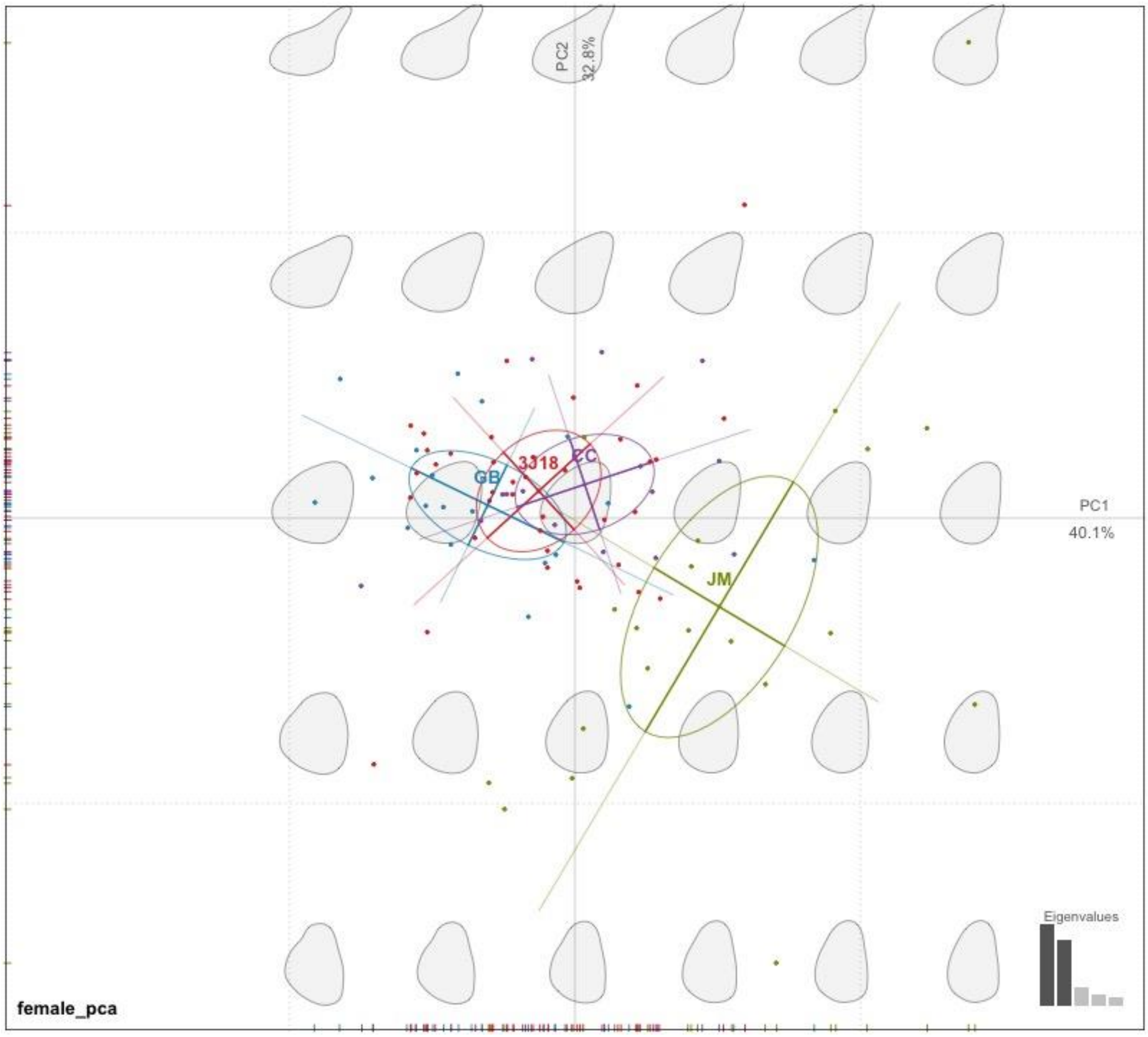


Figure 8.3.22 PC2 (horizontal axis) plotted against PC3 (vertical axis) by site for male individuals in a coordinate plane overlaid by site: JM=Jebel Moya, GB=Gabati, 3J18=3-J-18, and CC=Chichester, with 95% ellipses.

When examining the males by site in Figure 8.3.23, the first two principal component eigenvalues change again, this time to 38.5% and 25.9% (cumulative total 64.4%), respectively. As with the females, Jebel Moya remains separated from the other three sites, which remain in a cluster around (-x, 0). Gabati actually encompasses most of 3-J-18.

Figure 8.3.23 PC1 (horizontal axis) plotted against PC2 (vertical axis) by site for all individuals in a coordinate plane overlaid by site: JM=Jebel Moya, GB=Gabati, 3J18=3-J-18, and CC=Chichester, with 95% ellipses.

Next, Jebel Moya was examined alone. The principal components are once again different from the overall analysis: principal component 1 accounts for 40.8% of variation and principal component 2 accounts for 21.4% (cumulative total 62.2%). Principal component 1 in this case appears to be the posterior edge: on the positive end, the interosseous crest and posterior buttress form a unit more like that seen in the half-moon, while on the negative end they are small and separate. Principal component 2 appears to be the prominence of the most medial edge. In Figure 8.3.24, the females are mostly in (-x,y) while the males are mostly in (x,-y), and the ambiguous/unassigned overlap almost perfectly with the females.

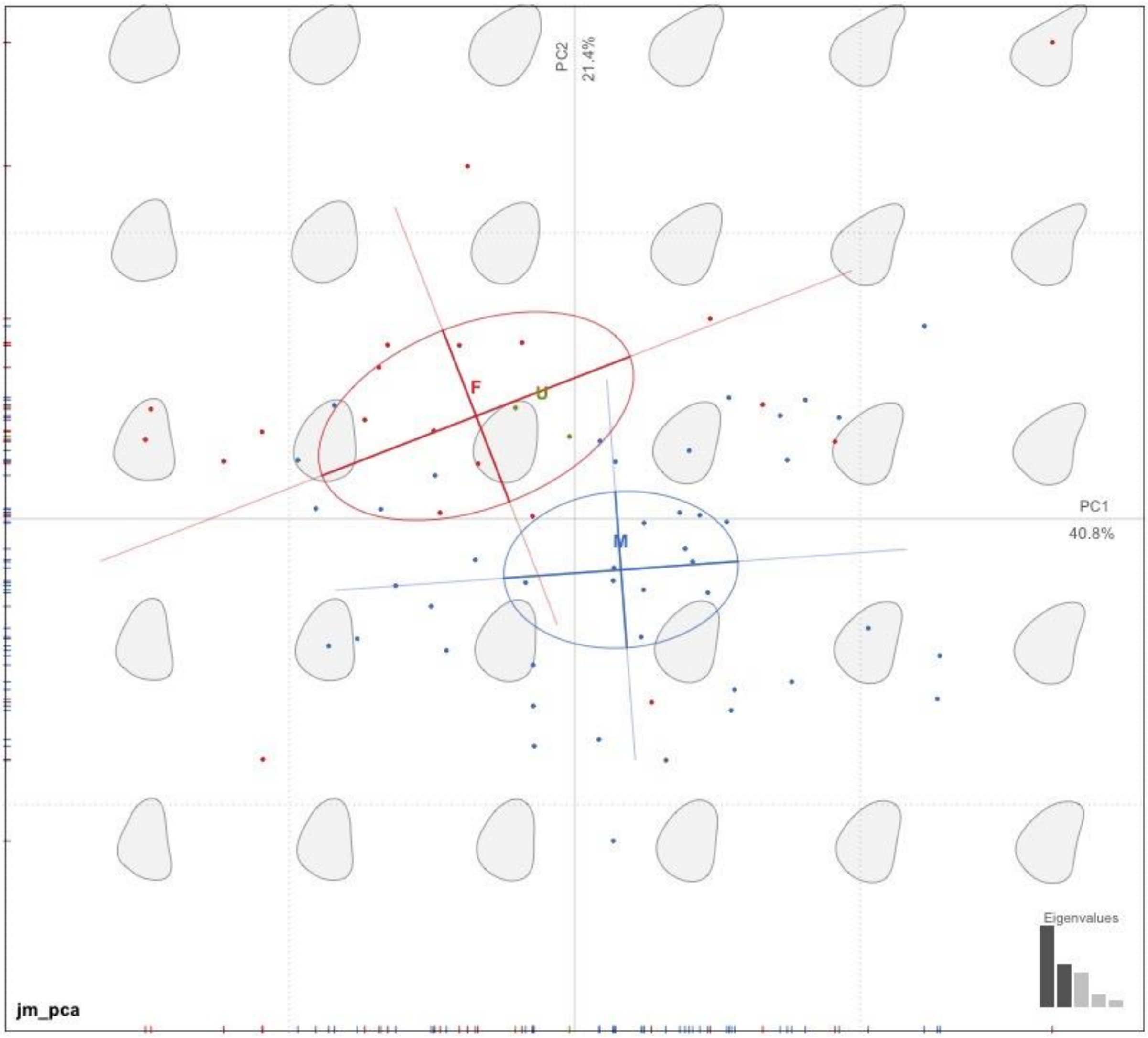


Figure 8.3.24 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all Jebel Moya individuals in a coordinate plane overlaid by sex: F=female, U=ambiguous/unassigned, M=male, with 95% ellipses.

Overlaying the coordinate plane with shape categories makes the patterns seen above clearer – the droplet shape category intersects the female area, while diamond, half-moon, flat side, and triangle overlap the male area, shown in Figure 8.2.25. Robusticity shows a similar pattern, with 0 and 1, the levels associated with females, overlapping (-x,y) and the rest in the (x,-y) and low (x,y) quadrants. Using principal component analysis has shown graphically the associations between sex, robusticity, and shape.

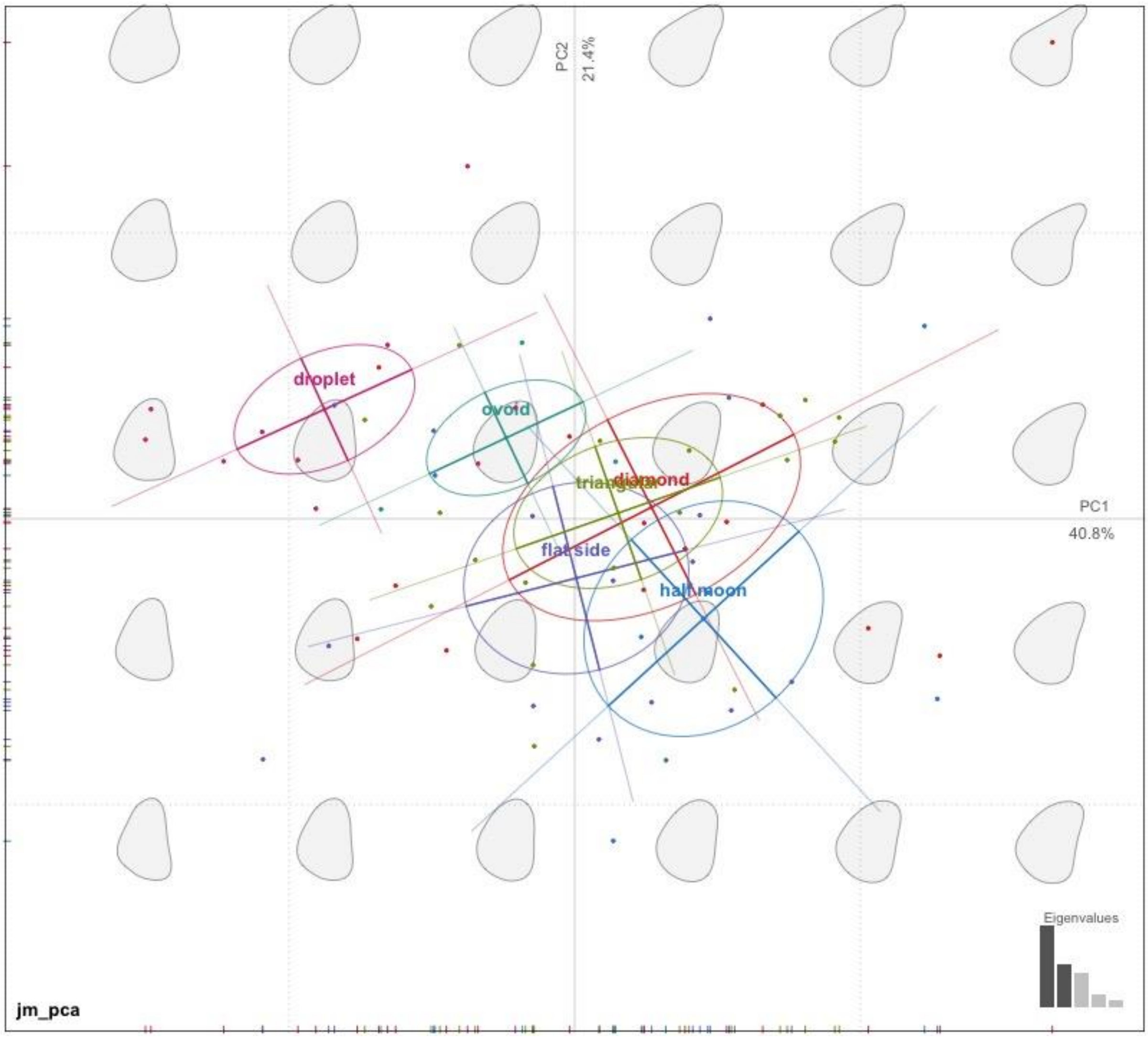


Figure 8.3.25 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all Jebel Moya individuals in a coordinate plane overlaid by shape, with 95% ellipses.

The other sites must be compared similarly. First, in 3-J-18, the principal components are once again different from the overall analysis: principal component 1 accounts for 47.2% of variation and principal component 2 accounts for 22.8% (cumulative total 70%). Principal component 1, examined further with shape amplification, is the curvature of the lateral edge: when externally curved on the negative end, the tibia is rounded in cross-section; when internally curved into a sulcus on the positive end, the tibia is triangular in cross section. Principal component 2 is the curvature of the medial edge with relation to anterior thickness. The difference between males and females, shown in Figure 8.3.26, is primarily based on principal component 1, with females towards negative (rounder) and males towards positive (more triangular). The individuals of unknown sex are in between, indicating a mix of males and females.

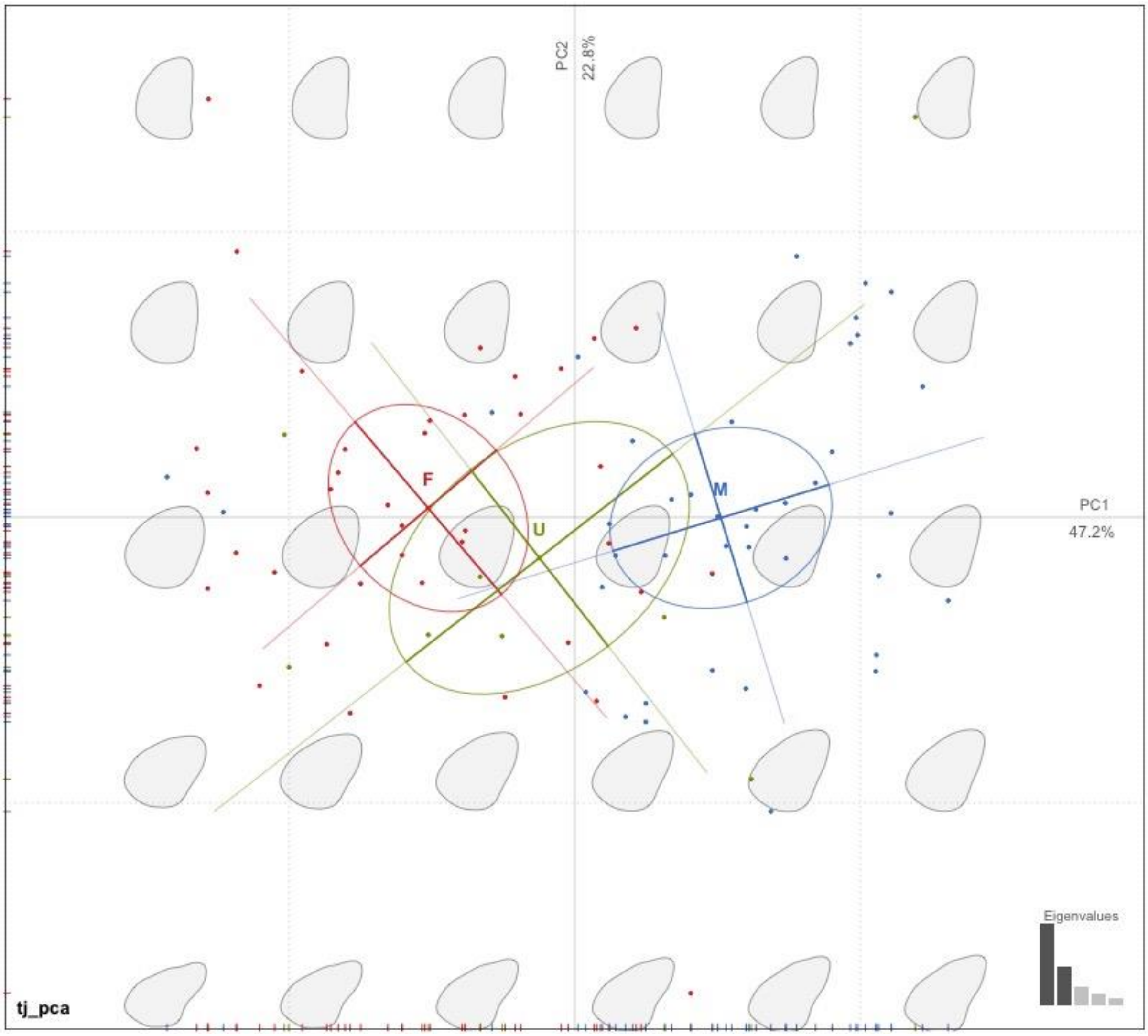


Figure 8.3.26 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all 3-J-18 individuals in a coordinate plane overlaid by sex: F=female, U=ambiguous/unassigned, M=male, with 95% ellipses.

Once again, when examined by shape in Figure 8.3.27, the droplet category overlaps where the females are in the previous figure, and the other categories cluster around where the males were previously. A similar result occurs with robusticity as above (not shown). Oddly, the triangular category ellipse only slightly intersects with female; equal numbers of 3-J-18 females are assigned to each category.

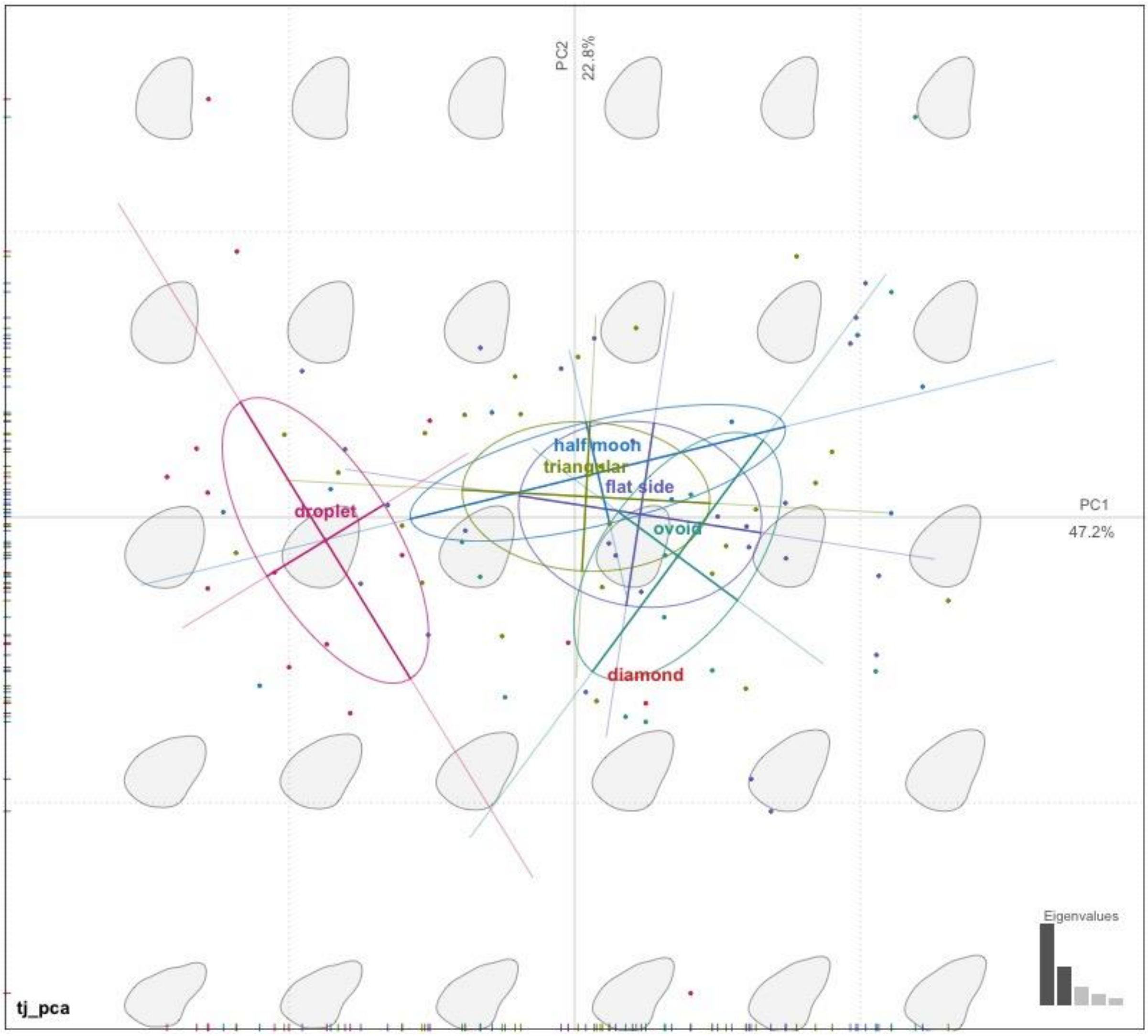


Figure 8.3.27 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all 3-J-18 individuals in a coordinate plane overlaid by shape, with 95% ellipses.

Since the age of 3-J-18 individuals could be estimated with a higher degree of certainty than those from Jebel Moya, age was examined with principal component analysis. However, the categories overlapped with no significant differences, as expected.

For Gabati, the principal components are also adjusted slightly, shown in Figure 8.3.28. Principal component 1 accounts for 58.7% of variation and is (as above) the curvature of the lateral edge. Principal component 2 accounts for 21.4% of variation (cumulative total 80.1%) and is the curvature of the medial side.

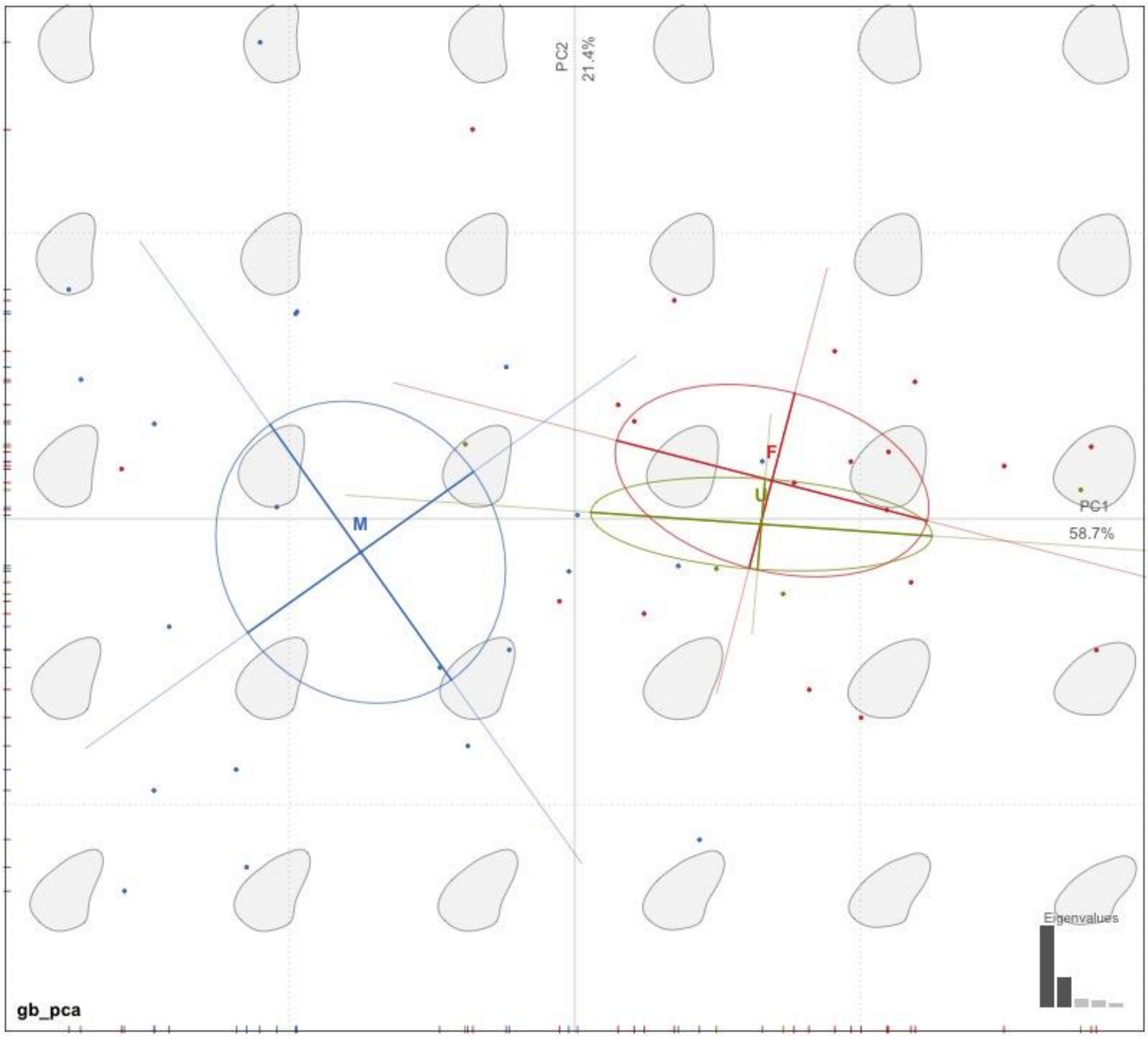


Figure 8.3.28 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all Gabati individuals in a coordinate plane overlaid by sex: F=female, U=ambiguous/unassigned, M=male, with 95% ellipses. Note that while the location of the sexes on the chart is reversed from Figure 8.3.26, the shapes are also reversed. This is due to slightly different PCs (noted on the axes), and they are mirror images of each other.

Shape was also examined in Figure 8.3.29 and, as seen at Jebel Moya and 3-J-18, droplet overlapped almost perfectly with female. Diamond encompassed the outlier males at (-x,y), and the other shape categories overlapped male towards the center or lay in between male and female, with some overlap of the triangular category. Robusticity (not shown) follows the patterns seen above, with 0 and 1 overlapping female and 2 and 3 overlapping male (the single individual scored as “4” was a male outlier in (-x,-y).

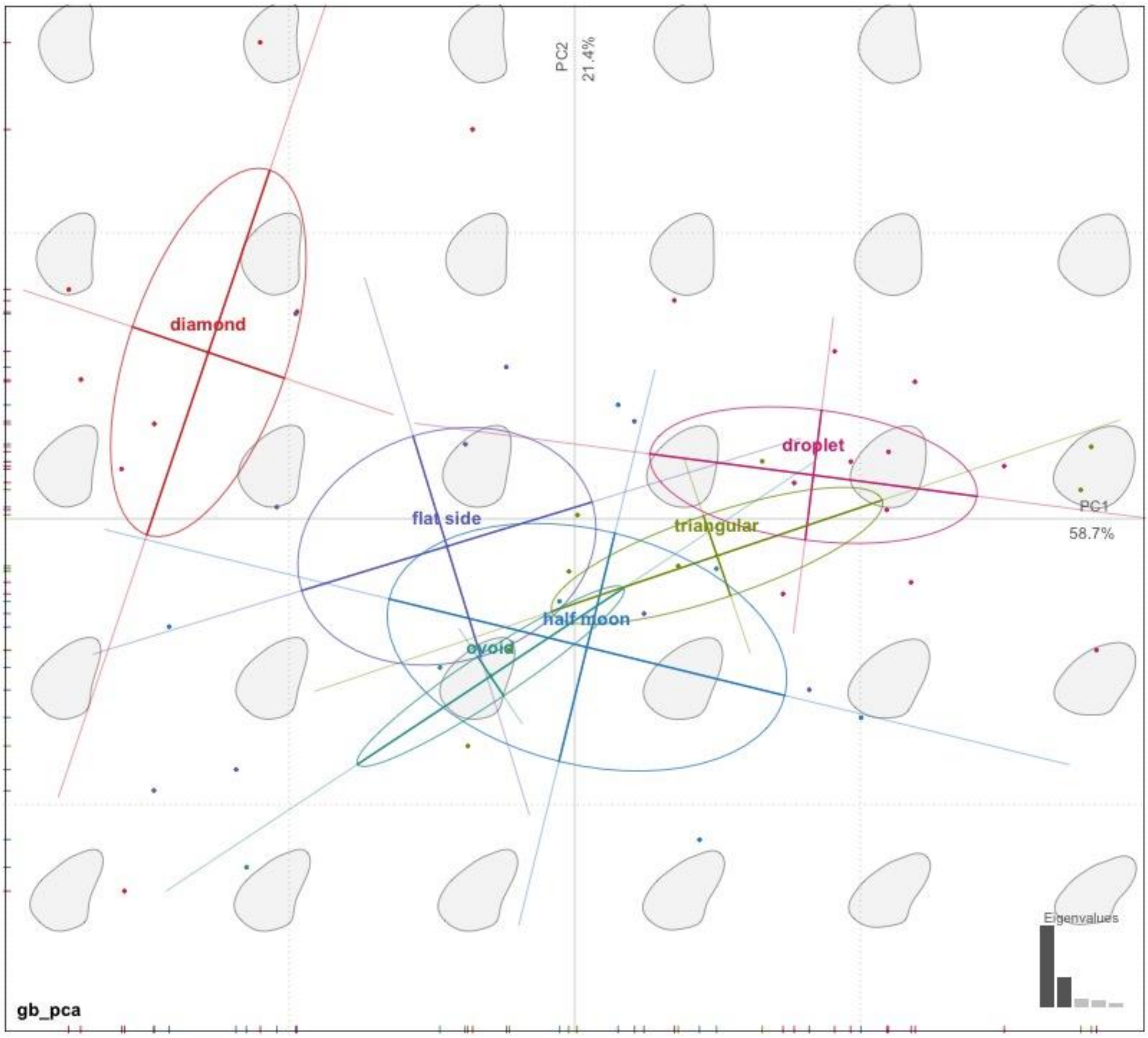


Figure 8.3.29 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all Gabati individuals in a coordinate plane overlaid by shape, with 95% ellipses.

Chichester results should be read with caution as the small sample size (n=42) may affect principal component analysis. Nevertheless, there is still a distinction between males and females, shown in Figure 8.3.30. Principal component 1 here accounts for 49.5% of the variation and is once again the curvature of the lateral side; principal component 2 accounts for 21.3% of the variation (cumulative total 70.8%) and appears to be medial length. Differences in the posterior side are not seen at all here.

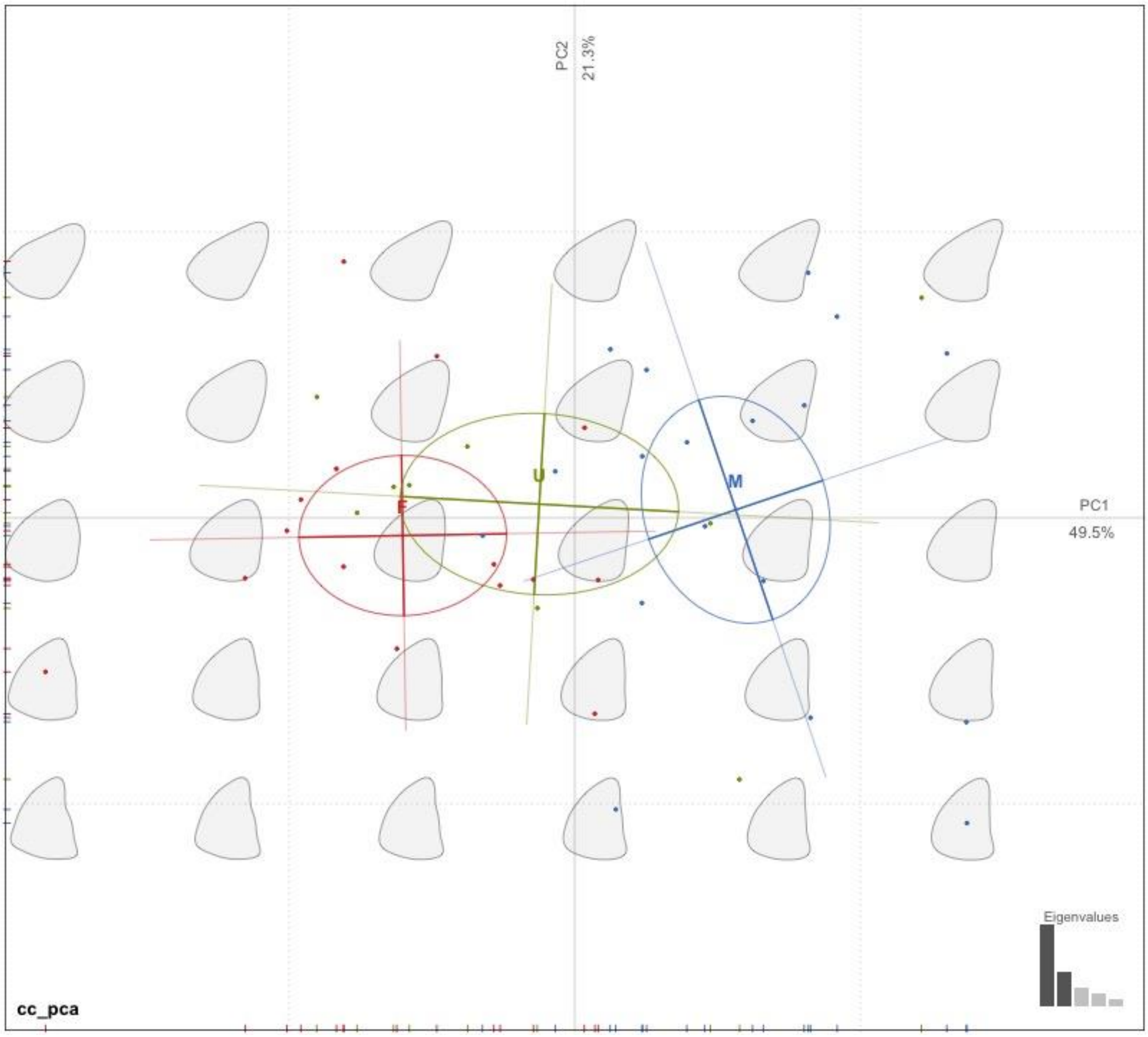


Figure 8.3.30 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all Chichester individuals in a coordinate plane overlaid by sex: F=female, U=ambiguous/unassigned, M=male, with 95% ellipses.

As there are no droplet-shaped female tibiae recorded at Chichester, the triangular category encompasses both female and ambiguous/unassigned (although the 2 droplet-shaped individuals fall into the female ellipse). The male area is overlapped by the half-moon, flat side, and diamond categories, shown in Figure 8.3.31. Likewise, the individuals with higher robusticity scores fall into the male area and those with low robusticity scores in the female and ambiguous/unassigned area (not shown).

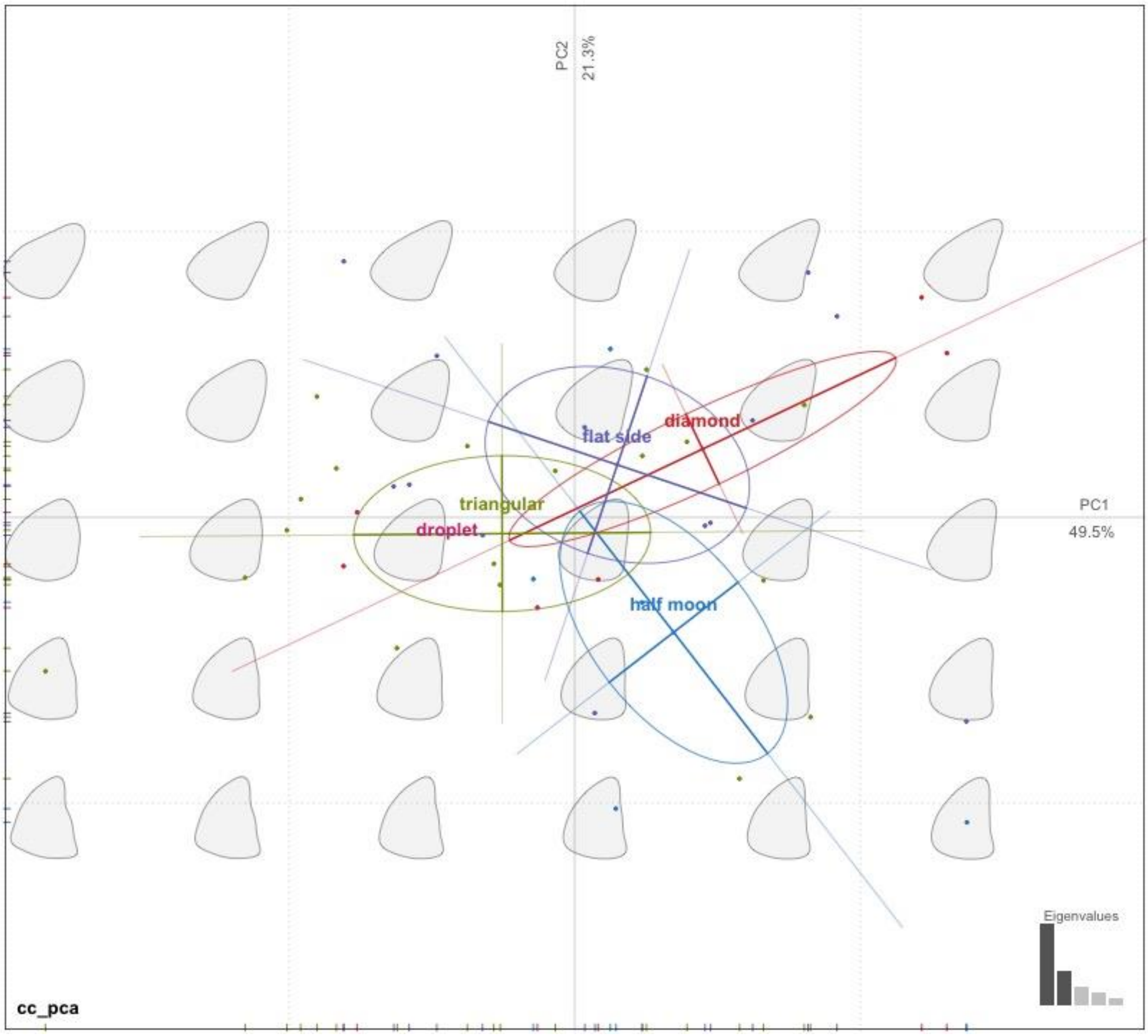


Figure 8.3.31 PC1 (horizontal axis) plotted against PC2 (vertical axis) for all Chichester individuals in a coordinate plane showing by shape, with 95% ellipses.

This chapter has presented the data from both CSG and GMM testing of the study groups. The interpretation and meaning of these results with be discussed in the next chapter, with an emphasis on how these data can be used to discuss ancient activity patterns in nomadic pastoral and agricultural societies within Sudan.

9 Discussion

The study presented here assessed and quantified the differences in midshaft tibial cross-sectional shape between individuals and groups from Sudanese archaeological sites practicing differing subsistence strategies. Other bioarchaeological studies have identified temporal shifts in tibial shape as defined by cross-sectional geometry and robusticity in other regions (Ruff and Hayes 1983; O'Neill and Ruff 2004; Nikita *et al.* 2011; Stock *et al.* 2011; Macintosh *et al.* 2014). This current work investigated individuals from roughly the same geographic region, northern and central Sudan, and time period, Meroitic to Medieval, in order to focus on activity-based differences, testing whether patterns of midshaft tibial shape can be associated with particular subsistence strategies on a population level.

This chapter will address the primary research objectives in light of the results presented in Chapter 8. First, a brief analysis of the results of the cross-sectional geometric and geometric morphometric analyses will be presented in sections 9.1 and 9.2, respectively. Using the interpretation of these results, each research objective will be addressed in section 9.3, focusing on whether the hypotheses were proven valid or null. Finally, this chapter will present the limitations of the dataset that could be improved in future research of this type.

9.1 Overview of cross-sectional geometry

This section will discuss the results of the cross-sectional geometric analysis. The variables compared were total area, polar second moment of area (J), maximum and minimum second moment of area (I_{max}/I_{min}), and anteroposterior and mediolateral second moment of area (I_x/I_y); see Chapter 7.4 for definitions of each.

Total area

Total area (TA) is highly correlated with cortical area, a measure of compressive strength; although cortical area tends to decrease with age, only eight individuals in this study (0.03%) were classified as "older adults" so normalization for age was not performed.

Individuals with higher TA will can be described as having more terrestrial mobility than those with lower TA (Stock and Pfeiffer 2004; Marchi 2008). The results presented in Chapter 8.2.2 showed that at all sites, males had higher TA than females even when standardised. This tendency was seen across all studies examining cross-sectional geometry (Ruff *et al.* 1984; Nikita *et al.* 2011; Macintosh *et al.* 2014; Marchi *et al.* 2011). While this difference could be ascribed to differences in activity levels – that is, males are more active than females across all human groups – it may also be due to inherent differences in human anatomy and needs more investigation focusing on comparing data from different sites worldwide.

The tibiae from Jebel Moya had the highest total area for both males and females (Figure 8.2.2). Standardising the data for estimated body mass meant that the tibiae from Jebel Moya also had the highest TA relative to size (Figure 8.2.3). Both Jebel Moya males and females had the longest tibiae but also the lowest estimated body mass. Using the standardised calculations, tibiae from Jebel Moya had the highest TA, followed by those from 3-J-18, then Gabati, then Chichester for males. For females, values at Chichester were higher than Gabati. Differences between TA at each site were significant for females and males, and the difference was most significant between Jebel Moya and the three agricultural sites (Table 8.2.5). Differences between Gabati and Chichester were also significant, but not between those sites and 3-J-18 (Table 8.2.6). In addition to their greater length, Jebel Moya tibiae had the highest compressive strength of all the assemblages, and tibiae from the sedentary agricultural groups had relatively lower compressive strength. This result was expected, as the general assumption in the literature is that agricultural groups have lower mobility and thus lower CSG values (Marchi 2008; Marchi *et al.* 2011). When investigating pastoralism and nomadism, discussed in Chapter 4, there is no set amount of mobility a group needs to accomplish: the distance traveled across the landscape varies by climate, herd animal, water availability, and sociopolitical associations (Cribb 1991; Fernandez-Gimenez and Le Febre 2006). It is possible that sedentary agricultural groups travel more on a daily basis to perform labour than nomadic pastoralists. However, in this case it does appear that Jebel Moya, the group argued to be nomadic pastoralists, had greater mobility. This will be explored further in this section utilising second moments of area and in section 9.3 utilising geometric morphometrics.

Considering individual variation instead of means, there were Jebel Moya female tibiae whose TA exceeded that of many males at the other three sites even when standardized for body mass. There were also more outliers at Jebel Moya than at other sites. Either Jebel Moya had more variation than expected – although the values are still normally distributed – or the sex of some individuals was incorrectly assigned. Alternately, not all individuals could be used in the standardised comparison as not all individuals have preserved femoral heads, so the data might be skewed to those preserved, which in many archaeological cases tend to be males as their larger size and skeletal robustness offers protection during deposition. Examining sexual dimorphism, Gabati tibiae had the highest rate (12.88%), followed by 3-J-18 and Chichester, with Jebel Moya at only 3.88%. Once again, Jebel Moya had the lowest rates of sexual dimorphism. This could be a result of more homogeneity within the Jebel Moya population than in the other examined groups, which is unusual considering many researchers' arguments that subsistence groups with high levels of mobility have high levels of sexual dimorphism (Ruff 1987; Larsen 1995; Marchi 2008). Another explanation for the low rate of sexual dimorphism at Jebel Moya and the high rate among the other Sudanese groups could be a combination of sex-based division of labour and differential food preparation and eating practices in these societies, although there is no archaeological evidence for this. Males and females at the sedentary agricultural sites may have had different diets, accounting for dimorphism in length and measurements, in addition to different activity patterns, accounting for the dimorphism in compressive strength. If this is accurate, it indicates more equality between males and females at Jebel Moya; however, it is difficult to compare these rates of dimorphism to other publications as dimorphism can vary greatly depending on the bone, body part, or system compared, and most researchers do not publish the equations used. Further, some researchers use a different calculation relating the female in terms of the male rather than percentage difference between the two. Larsen estimates that humans have an average dimorphism rate of 15% (2003), but does not define what data were used in that assessment.

In an ANOVA performed on the midshaft shape categories (Table 8.2.7), further patterns emerged. The droplet-shaped category was significantly different from the others in TA: tibiae in that category had the lowest mean TA, while tibiae in the diamond category had the highest TA, although there was overlap in TA between categories. Note from above that the droplet shape and low TA were associated with females and the diamond shape and high TA with males. It is still unclear at this point whether the shape categories are related to sex, strength, or a yet-undefined variable that provides the quantitative link between shapes.

Polar second moment of area

The results for *J*, presented in Chapter 8.2.3, mostly mirrored the results for TA and all conclusions for TA are thus applicable to *J*. As with TA, males consistently had higher *J* than females at all sites, and Jebel Moya males and females have higher *J* values than those at the other three sites. Standardisation based on estimated body mass reduced Jebel Moya's significant difference in length to align more with the others, but the Jebel Moya values were still much higher. In descending order, the next highest for males were Chichester, Gabati, then 3-J-18; for females, 3-J-18 is higher than at Gabati (Figure 8.2.10). There was a lack of correlation between length and standardised *J* (Figure 8.2.11). An ANOVA showed that there was a significant difference in *J* between sites for males and for females (Table 8.2.12). In addition, the difference between each of the three agricultural/sedentary sites was less significant than the difference between each of them and Jebel Moya (Table 8.2.13). However, the difference between Jebel Moya and Chichester was not significant.

Examining shape, the results replicate those of TA: the droplet-shaped category had the lowest mean *J* and the diamond-shaped category the highest mean *J*, with significant differences in *J* between droplet and a number of other groups (Table 8.2.14). Both TA and *J* showed that Jebel Moya tibiae had greater strength (both compressive and torsional), and that there was a range of values within each site based on sex and assigned shape, with female values lower than male values and droplet values lower than diamond values.

Second moment of area in the maximum-minimum planes

The sites were all roughly equal in I_{max}/I_{min} distribution (Figure 8.2.16). Again, male individuals tended to have significantly higher circularity indices than female individuals (the difference is significant), but there was also overlap between the male and female values. Jebel Moya had the highest value and Gabati had the lowest, but the differences between sites were not significant. This indicates that circularity was not site-dependent: there were individuals from all sites with more "circular" tibiae and individuals with more elongated tibiae. This was unexpected, as Jebel Moya had higher values for TA and J and one would expect the trend to continue with I_{max}/I_{min}.

In contrast, analysis of shape provided more detailed and anticipated results. Examining by shape using geometric morphometrics presented a more nuanced analysis. The ovoid-shaped tibiae had the highest I_{max}/I_{min}, significantly more so than the other categories. Droplet-shaped tibiae had the lowest mean I_{max}/I_{min}, but triangular-shaped tibiae had the lowest values (Figure 8.2.18). The ovoid-shaped tibiae were extremely elongated, while triangular (and similarly, diamond and half-moon) were more equal in maximum and minimum dimensions, demonstrated by measurements of the anteroposterior and mediolateral diameters. Again, the Gabati and 3-J-18 female tibiae had the lowest mean TA and were also droplet-shaped, demonstrating the link between sex, CSG properties, and shape in this instance.

Second moment of area in the anteroposterior-mediolateral planes and theta

I_x/I_y, presented in Chapter 8.2.5, indicates circularity in the anteroposterior-mediolateral plane. The results were varied and did not correlate with those of I_{max}/I_{min} (Figure 8.2.18), revealing large ranges for Chichester females and Jebel Moya males (Figure 8.2.16) and few significant differences between groups (Table 8.2.17). As suggested in the results, it was difficult to interpret these in line with any of the other CSG results.

Theta describes the angle between the maximum plane and the mediolateral plane (Ruff and Hayes 1983). The greater the angle of theta, the further from an "anatomical" axis and the greater error in second moment of area may be, particularly for I_y (O'Neill and Ruff 2004). This may explain the differences between I_{max}/I_{min} and I_x/I_y. There was a significant difference between theta at each site for both sexes, and females tended to have both lower and higher theta values than males. Although a linear regression equation was able to predict theta from I_x/I_y (Table 8.2.19), it was not a strong correlation.

The results from cross-sectional geometric analysis of the tibiae showed significant differences between sites and sexes for total area and polar second moment of area, and significant differences between sexes for second moment of area in the maximum-minimum planes. Second moment of area in the anteroposterior-mediolateral planes did not show significant differences. Overall, the tibiae of males and females from Jebel Moya tended to have higher values for TA and J than 3-J-18 and Gabati, indicating higher mobility among the nomadic-pastoral group than the agricultural groups. The next section will discuss the shape categories referred to above using geometric morphometrics.

9.3 Geometric morphometrics

This section quantifies the difference between shape categories using geometric morphometrics instead of cross-sectional geometry. Later, these data will be used to determine whether the shape categories, originally proposed by Hrdlička and used in a slightly altered form here, are biologically valid categories useful in further analyses of tibial midshaft shape.

Landmark analysis

Landmark analysis within Morphologika, presented in Chapter 8.3.1, allowed the examination of principal components of six landmarks. Principal component analysis (PCA) identified that the first principal component (PC1), or the feature accounting for most of the variation, was how anterior the most medial point was, and the feature accounting for the second-most variation (PC2) was the height of the interosseous crest, varying between a flat-side shape and point closer to the anterior crest (Figures 8.3.3. and 8.3.4). However, as the pilot study showed that six-pointed landmark analysis is not precise enough, the rest of the analyses were performed on the entire outline.

Outline analysis

Outline analysis, performed with the Momocs program for R, identified the same principal components as in landmark analysis. The first principal component (PC1) was once again the medial side (Figure 8.3.8). A positive PC1 did not roundly protrude towards the medial side as much as a negative PC1, influenced by the posteromedial angle. Additionally, negative PC1 shapes had rounder edges and positive PC1 shapes had sharper edges. The second principal component (PC2) was the depth of the lateral sulcus, which could not have been illustrated by landmark analysis as performed above, as the six points could only be connected by straight lines rather than curves. The third principal component (PC3) was triangularity: a positive PC3 had rounded medial and posterior sides and trended towards four external angles while a negative PC3 had flatter medial and posterior sides, a sharper posteromedial angle, and trended towards three external angles (Figure 8.3.9).

Overlay of experimental groups onto the principal component planes highlighted distinct subgroups. Females and unassigned individuals trended towards negative PC1 and slightly positive PC2, or sharper edges and shallow lateral sulci, while males trended towards positive PC1 and neutral PC2, or rounder edges and deeper lateral sulci (Figure 8.3.10). This indicated that male tibiae had a less prominent medial border than females but a slightly deeper lateral sulcus. The unassigned individuals plotting close to the females was likely due to the probability of the unassigned individuals being female in two of the assemblages, Jebel Moya and 3-J-18. Comparing the third principal component, females had more rounded medial and posterior sides than males and less distinction between the posterior and medial sides (Figure 8.3.11). These three principal components accounted for 80.11% of the variation, which is an acceptable quantity in these types of analyses (Hatcher 1994; Beaumont 2012). A multiple analysis of variance for the first three principal components found that the difference between males and females are significant, but that the difference between females and unassigned was not significant (Table 8.3.12), supporting the argument that many of the unassigned individuals could be female.

Principal component analysis performed for soleal line robusticity scores showed a similar grouping pattern to sex, above (Figures 8.3.13 and 8.3.14). Low robusticity scores tended to be negative for PC1 and neutral for PC2, echoing the female group with a more prominent medial border, while higher robusticity scores tended to be positive for PC1 and negative for PC2, echoing the male group with a deeper lateral sulcus and less prominent medial border. The moderate robusticity scores formed a slight arc between them into positive PC1 and positive PC2. The individuals with a more robust soleal line also had a deeper lateral sulcus. There may be a muscular or biomechanical connection between the pronounced interosseous crest that accompanies a deep lateral sulcus and the muscle bellies of the *soleus* and *gastrocnemius*.

Principal component analysis performed for shape categories supported the patterns described above (Figure 8.3.16). The droplet shape category – for which CSG values and robusticity scores were low and was strongly correlated with females – was found to be negative for PC1 and positive for PC2, indicating a prominent medial border and more rounded edges. The ovoid, triangular, half-moon, and flat-side shapes mostly overlapped around the origin, but the diamond shape was positive for PC1 and neutral for PC2. It was significantly different from the droplet shape category (Table 8.3.18). Additionally, the axes of these categories were oriented at skew angles to the main axis, indicating a slightly different shape alignment. When PC3 was considered, there was less of a distinction between the categories, indicating that the number of angles (triangular versus diamond shape) accounted for more variance than anterior breadth.

The difference between sites was examined using principal component analysis. Similar to the patterns observed in CSGs, Jebel Moya was distinct from the other three sites. PC1 and PC2 were positive for Jebel Moya individuals, indicating a flatter medial side and a deeper lateral sulcus, while Chichester, 3-J-18, and Gabati were neutral for PC2 and negative for PC1, indicating slightly more prominent medial side and, while not lacking a lateral sulcus, the sulci were not as deep (Figure 8.3.19). Note that Jebel Moya had a higher proportion of diamond-shape tibiae than the other sites, and when overlaid with the shape coordinate plane, the 95% ellipses of diamond-shapes and Jebel Moya individuals overlapped and both had the negative-skew axis of orientation. A multiple analysis of variance on these principal components confirmed that the differences between groups were statistically significant except between 3-J-18 and Gabati.

When examining principal components of only females, there were some slight differences in the amount of variance accounted for by each component and the shape they accounted for (Figure 8.3.22). While PC1 remained the same, PC2 had been inverted. The results still showed distinct differences between Jebel Moya females and females from the other three sites. Jebel Moya was negative for PC2 and positive for PC1, indicating a less prominent medial edge and lacking a lateral sulcus, while the other sites were negative on PC1 and neutral on PC2, indicating a more prominent medial edge and a small lateral sulcus. Analysis of only males exhibited the same result (Figure 8.3.23).

These patterns were seen again when examining Jebel Moya alone (Figure 8.3.24). Females had negative PC1 and positive PC2, an area that overlapped with droplet and ovoid shapes, while males had positive PC1 and negative PC2, overlapping with the other shape categories. Unassigned individuals fit inside the female 95% ellipse. Very similar results were observed at the other three sites: low soleal line robusticity, droplet and ovoid shape, and female sex had prominent medial sides, rounder angles, and a shallow lateral sulcus, while high soleal line robusticity, diamond, flat-side, half-moon, and triangle shape, and male sex had sharper angles and a deep lateral sulcus. Additionally, these features were associated with CSG values as predicted by linear regression. Each analysis showed a strong correlation between shapes, sex, robusticity, and cross-sectional geometric properties.

9.3 Research objectives

This section addresses the research objectives presented in Chapter 5 utilising the results of this study.

Does tibial midshaft shape vary within the examined assemblages, between and within assigned sexes, and between different estimated ages of adults?

Yes, tibial midshaft shape, whether defined by CSGs or morphometrics, varied between the examined assemblages. Jebel Moya was more robust, had higher total area and polar second moment of area (thus higher bending and twice torsional rigidity), and more individuals with the diamond-shape tibial cross-section than the other groups, which can be associated with walking or running long distances. 3-J-18, Gabati, and Chichester were more similar in their CSGs (Figures 8.2.2, 8.2.9, and 8.3.19). Tibial midshaft shape varied greatly between sexes. Males had higher CSGs than females at all sites (Figure 8.2.2), were more robust (Figure 8.1.37), and had more variation in shape distribution. Male tibiae were more evenly distributed between shape categories while female tibiae were mostly droplet and triangular (Figures 8.1.15, 8.1.20, 8.1.27, and 8.1.32). Individuals of estimated age only differed in robusticity scores, with middle adults slightly more robust than younger adults; no difference was seen in CSGs or morphometric variation, as there were too many adults unassigned to an age stage.

The number of individuals at Gabati and the assignment of individuals to time periods allowed further intra-site comparison. Directional and absolute asymmetry, presented in Table 8.1.24, were examined at Gabati due to that site's high level of preservation of both tibiae. Although there was a 0.08% right-side bias for length, total area showed a left-side bias of 1.25%. Statistical tests found no significant difference between left and right sides, so any differences were most likely random variation and suggest a lack of unilateral activities using the legs (Nikita *et al*. 2011). This supported the conclusion drawn from the pilot study in Chapter 7 and from previous work indicating that human lower limb asymmetry is overall lower than upper limb asymmetry (Stock and Pfeiffer 2004; Wanner *et al.* 2007). Gabati also offered the opportunity to divide the sample into time periods, Meroitic, Post-Meroitic, and Medieval, based on archaeological analysis of grave superstructures. As the periods at Gabati spanned the introduction of the *saqia* water wheel that would have potentially decreased the amount of labour involved in field irrigation, one of the research objectives was to compare midshaft tibial shape and CSGs across time periods to test for evidence that implementation of the *saqia* wheel had a detectable impact on activity levels. As shown in Table 8.1.25, when further divided by sex, the time period categories were too small to elicit any significant findings. As there were more females in the post-Meroitic and Medieval periods, the droplet shape (the criteria for which are defined in Chapter 7.6) was more prevalent than in the Meroitic period. Therefore, definitive conclusions cannot be made regarding activity practices in the three time periods, and the question of the effect of *saqia* wheel implementation at Gabati remains unresolved.

These data indicate that the hypothesis for this objective is supported by the data.

Can the different assemblages consistently be separated by midshaft tibial shape? If so, is there a typical shape for each?

No, the assemblages cannot be concretely separated by the six midshaft tibial shape categories. There was too much overlap in the number of individuals in each group with each shape. For example, both males at Jebel Moya and Chichester had a high percentage of triangular tibiae (31.3% and 38.9% of males, respectively), and females at Jebel Moya, 3-J-18, and Gabati all had high proportions of droplet-shaped tibiae (35%, 31.6%, and 54.2% of females, respectively). Principal component analysis improves the researcher's ability to segregate groups, however: Jebel Moya continually stood out in the analyses as a separate group with little overlap. This type of analysis can help define what could be a semi-nomadic/sedentary divide: the former had a deeper lateral sulcus and a higher likelihood of having a posterior buttress, while the latter lacked these features (Figure 8.3.8). Further, males and females can be easily segregated using principal component analyses and, to an extent, shape. Droplet-shaped tibiae had a higher chance of belonging to females, and diamond and half-moon to males (Figure 8.3.10). The triangular category was often evenly divided, particularly at Chichester, and so could not be used to indicate sex. These data indicate that the hypothesis for this objective is correct: as there are potentially many activities that could result in the same shape, and the processes by which bone shape develops are not completely understood, it is unlikely that any one group will ever have a completely distinct tibial shape.

Do assemblages from sites with similar subsistence strategies have more similar midshaft tibia shapes than those with dissimilar strategies?

Yes, the three sedentary (and theoretically, urban/agricultural) sites were more similar to each other than to Jebel Moya (for example, see Figures 8.2.2, 8.2.9, and 8.3.19). Although it is unclear whether Chichester practiced agriculture – as a coastal town, there might be fishermen, merchants, and individuals practicing a variety of professions – but it is likely the individuals at Gabati and 3-J-18 were not exclusively farmers either. Gabati had a high proportion of diamond-shaped male tibiae as well, indicating higher mobility for a small group of males. A variety of tibial shapes indicates a variety of activities. Jebel Moya also had tibiae of a variety of shapes; the distribution of shapes was not markedly different except for the high proportion of diamond-shaped tibiae, but they had consistently higher CSGs. The difference between the females with triangular tibiae, represented in a high proportion at Chichester but low at the Sudanese sites, and the females with droplet tibiae could use more investigation, especially since those females at Jebel Moya were taller and had higher CSG values. Chichester was chosen here as an outgroup: as described in Chapter 6.3.4 and Chapter 8.1.5, the individuals there were buried shortly after Medieval Gabati and 3-J-18, but the site differed in genetic composition, environment, and climate (Adams 1997). The data on repetitive activities practiced by individuals buried in the Chichester cemetery is limited, likewise at Gabati, 3-J-18, and Jebel Moya. However, there is no evidence that the people of Chichester were nomadic pastoralists, and highly likely they were mostly sedentary as suggested by parish records (Hart *et al.* 2012), aligning them with the Nile-adjacent Sudanese groups. The tibiae of the Chichester individuals were slightly shorter than those at 3-J-18 and Gabati (for males, 370 mm, 390.8 mm, and 382.8 mm respectively), but had greater estimated body mass (70.37 kg for men) than at any of the Sudanese sites including Jebel Moya (64.04 kg). However, CSG properties at Chichester were in the same range as those of the two Sudanese sedentary sites, shown in Table 8.2.1. In addition, the shape distribution was similar to those sites, although there was less variation between males and females. Despite differences in body mass, region or ecological zone, and probably genetic makeup, the similarities seen between Chichester and the sedentary sites of 3-J-18 and Gabati, alongside their difference from Jebel Moya, can most likely be ascribed to differences in activity. If the differences in tibial morphology were strictly genetic or regional, the expected result would be a greater similarity between Jebel Moya and the Sudanese sedentary sites, and a greater difference between all three Sudanese sites and an English town. This is not the case. This adds to the argument that there are noticeable and quantifiable differences in tibial measurements and CSG properties between groups practicing differing methods of subsistence (Table 8.2.1).

Further, it is not likely that these shapes can be associated with any particular activity or "profession". As discussed above, the long-distance runner, the mogul skier, the Amud Neanderthal, and many of the Jebel Moya males all had diamond-shaped tibiae. However, previous biomechanical analyses can be used to explain these shapes generally. The diamond and ovoid are indicative of primarily anteroposterior loading, the droplet and triangular equal loading (or unloading), and the flat-side and half-moon mediolateral loading. There is enough variety particularly with females to argue that some individuals walked extensively. If the entire group was semi-nomadic, one would expect that all individuals would have higher anteroposterior loading, but this is not the case. Either not all individuals walked as far – perhaps indicating divisions of labour with herding – or some individuals were more nomadic and some more sedentary. In the agricultural groups, as mentioned above, there were probably many activities performed and researchers will likely never be able to ascertain exactly who performed them or for how long. The conclusion from the data presented here is that fewer individuals in sedentary, agricultural groups experienced the tibial changes associated with high anteroposterior loading typical of walking or running long distances.

Robusticity can also be addressed in this context. Robusticity of the soleal line was compared between males and females in Chapter 8.1.6. As expected based on the results of other studies on musculoskeletal markers, (Churchill and Morris 1998; Pearson 2000; Weiss *et al.* 2012), females were overall less robust than males. The few females with higher robusticity scores were all from 3-J-18, while the males with higher scores were from both 3-J-18 and Gabati. Jebel Moya tibiae were mostly scored "slight" robusticity despite being longer with higher TA. As discussed in Chapter 3, many studies have linked robusticity with amount of activity performed (Hawkey and Merbs 1995; Robb 1998). If this is a correctly-interpreted correlation, the conclusion from these assemblages is that females performed overall less activity than males, females at 3-J-18 performed more activity than females at other sites, and all individuals at Jebel Moya performed less activity than all individuals at other sites. This is counter to the assumptions made about pastoral populations, particularly that they are more frequently mobile than sedentary populations (Ruff *et al.* 1984; Pearson 2000; Marchi 2008). Additionally, a correlation was seen in males between age and robusticity: older males tended to have higher robusticity scores. This correlation was not seen in females. This could be due to the lifelong production of testosterone in males but not females, which could continue to stimulate osteoblast production and bone remodeling into middle age (Falahati-Nini *et al.* 2000). Females do not have this protective testosterone, which may limit bone remodeling and at menopause can lead to osteopaenia and osteoporosis, pathological changes experienced by males only in old age (Stini 1990; Kujala *et al.* 2000). As previous studies mentioned in Chapter 3.5 reported, the difference in robusticity or CSGs is often less significant between time periods for females than for males (Churchill and Morris 1998; Nikita *et al.* 2011; Weiss *et al.* 2012; Macintosh *et al.* 2014). Perhaps this is indicative of hormonal differences in bone formation rather than a difference in activity patterns. Individuals prone to bone formation, discussed in Chapter 3.6, must also be considered, particularly when there are occasional individuals with very high levels of excessive bone formation (Rogers *et al.* 1997; Waldron 2009). Robusticity needs to be investigated further, and ideally males and females should be examined separately as the hormonal causes of musculoskeletal robusticity could be as important to this discussion as activity and stress.

As these sites were chosen as representatives of their subsistence strategies, these arguments could potentially be extrapolated to other sites in the Nile region and beyond. Nomadic pastoralist males have high scores for soleal line robusticity, higher cross-sectional geometric values than sedentary males, and a high proportion of the tibial cross-sectional shapes indicating anteroposterior loading relative to other shapes, in addition to low rates of sexual dimorphism in the legs. Sedentary/agricultural males have lower robusticity and cross-sectional geometric values than nomadic pastoralist males and higher proportions of shapes indicating mediolateral loading and higher rates of sexual dimorphism. Females display less difference in shape than males, possibly due to hormonal influences on bone remodeling and muscle development. However, the nomadic pastoralist females have higher CSG values than sedentary/agricultural females. These differences could possibly be added to other archaeological data such as botanical and faunal remains to form an argument for a group practicing a particular subsistence strategy. The data indicate that the hypotheses for this objective are supported. However, a limitation is that only one nomadic-pastoral group was examined. This is due to a lack of skeletal remains of nomads in general and Sudanese nomads in particular without differing too drastically from the similar ecological zones. Studies of more nomadic and pastoral groups worldwide might show similar patterns of mixed mobility, but these were not explored here to limit the geographic focus.

Do cross-sectional and morphometric approaches yield similar patterns of variation, similarity and difference?

The study sought to investigate the differences between cross-sectional geometry and geometric morphometrics. While the former identified that Jebel Moya has significantly higher total area and polar second moments of area (thus higher rigidity) than the other three groups (Table 8.2.5 and 8.2.12), the method was unable to discriminate between groups, particularly with the second moments of area. I_{max}/I_{min} comparisons were not effective in differentiating sites, although they were correlated with shape categories (Figure 8.2.16); I_x/I_y was not strongly correlated with any other values in this study (Figure 8.2.18). Geometric morphometrics was able to discriminate some groups within the data as well as elucidate the particular differences between them (Chapter 8.3). It is useful to ask what CSG is accomplishing in many studies: is it essentially investigating platycnemia more scientifically? Here, it shows that, for example, Jebel Moya males have higher torsional strength than Gabati males, indicating a higher level of activity. With the integration of geometric morphometrics, it is possible to see that there is a shape difference not explained by I_{max}/I_{min} but that could be explained by examining the surrounding musculature and comparing the shape to existing studies of both archaeological groups and modern active human subjects. Thus geometric morphometrics with principal component analysis can be seen as a more nuanced approach to examining tibial midshaft shape. Using both approaches can answer further questions about the relationship between shape and strength. For instance, the droplet shapes had the lowest TA and *J* and diamond shapes the highest. By linking these with assigned sex, it is possible to develop a more complete hypothesis of how bone adapts shape in response to activity.

Can tibial diaphyseal shape be used to infer past activity patterns in ancient societies?

It was possible to conclude that some individuals were performing more activity in a certain direction (from geometric morphometric analyses) and that some were performing more overall activity (from CSG analysis), but as expected based on previous research and the body of literature examined, it was not possible to identify discrete activities. The data presented here clearly show that the individuals buried at Jebel Moya were performing more overall activity and that some individuals were highly mobile, and the individuals buried at 3-J-18 and Gabati performed less overall activity with fewer highly mobile individuals. This could be connected to herding behaviour and the proportion of individuals required for this task, or to population movement, with more individuals moving between seasonal sites rather than staying in one urban settlement. Alternately, as external diaphyseal shape and bone density are reflective of activities performed in the peripubertal period (Grimston *et al.* 1993; Lieberman *et al.* 2003; Morseth *et al.* 2011), the individuals with high mobility at Gabati and 3-J-18 could have had a more mobile youth before their settlement or burial at these sites. Considering that the cemeteries cover a few centuries, it was not possible to determine how many individuals were highly mobile at any one time.

The study sought to investigate whether the shape categories are biologically valid and can thus be used to discriminate activity. As discussed above, the categories are taken from Hrdlička's observational studies from the early 1900s with minor alterations. The midshaft shape categories must be assessed considering the surrounding muscles and fascia as well as axial forces acting on the bone in compression, bending, and torsion. First, forces on the bone from repeated activity have been shown to change the bone's shape in cross-section, and studies of athletes revealed distinct shape variations as a result of practicing repeated activity at critical stages of bone growth. In particular, Shaw and Stock's midshaft CT scan

(2009) of the tibiae of athletes can be examined in this context, with the tibia of a long-distance runner assigned to the diamond category, the control assigned to triangular, and the hockey player assigned to flat-side. The tibiae in Nikander's similar study (2008) can be similarly assigned – the tibia of the mogul skier to ovoid and the slalom skier to flat-side. The robust tibia from Broken Hill (Trinkaus *et al.* 2009) can be assigned to diamond as well. The tibial scan presented in Cooper *et al.* (2008) can be assigned to flat-side and the tibia in Bergman *et al.* (2004) can be assigned to half-moon, but the authors do not state the activity practices of the individuals. If midshaft cross-section shapes are solely the result of longitudinal forces, and the triangular shape seen in the control and in juvenile tibiae is the basic genetically-determined shape as suggested by Lanyon (1980), one conclusion drawn by previous researchers is that loading in the anteroposterior direction increases rigidity in that direction, extending the tibia along the anterior edge and altering it to the diamond shape; loading in the mediolateral direction increases rigidity in that direction, extending the tibia along the medial and lateral edges and altering it to the flat-side or half-moon. Variations on these activities, with differences in intensity and directionality, could result in the variety of shapes suggested by Hrdlička and identified here. This scheme can be summarised as bones adapting to purpose by remodeling in the direction of greatest stress, or the "biomechanical hypothesis". However, none of these account for the droplet shape seen most commonly in females in this study. A probable explanation is that the droplet shape, rather than the triangular outline commonly associated with the tibia, is the juvenile shape and the shape that is retained into adulthood when unstressed (or lacking the hormonal signatures to remodel when stressed).

It is equally important to examine the musculature surrounding the tibia, shown in Figure 2.3.2. As the research above showed, diamond-shaped tibiae in this study were correlated with high scores for soleal line robusticity. Similarly, Busk noted in the 1870s that the platycnemic tibiae were also robust (Lucas 2007), Broca observed the same of Cro-Magnon specimens (1880), Turner commented that shape change might be due to muscle traction (1895), and Buxton argued that an overly prominent *tibialis posterior* resulted in platycnemia (1938). Endo and Kimura (1970) suggested that the diamond shape of the Amud tibia is due to the *popliteus, soleus,* and *flexor digitorum longus* being situated in a more anterior location than in modern specimens: while it is possible for muscle attachment sites to vary, another explanation could be that these muscles are especially prominent. There has been little research apart from Lanyon (1980; 1987) on the result of muscle atrophy on bone in the absence of bone atrophy. Lanyon's work showed that tibial shape is highly dependent on the surrounding musculature, finding that lack of muscle development resulted in a tibia with convex posterior, medial, and lateral sides and rounded angles. In a natural environment – that is, without the neurectomy in Lanyon's study – it is possible that lack of muscle development and the accompanying local surface loads of muscle bellies could result in more rounded, less sharply-angled tibiae like those of the droplet shape. Conversely, larger muscles might press more strongly onto the bone surface, resulting in the concave surfaces seen in the half-moon and flat-side shapes. These muscles *flexor digitorum longus* at posteromedial, the *tibialis posterior* at posterolateral, and *tibialis anterior* at anterolateral are all largest at approximately midshaft. The depth of the lateral sulcus could be the result of a large *tibialis anterior*, possibly linked to a strengthened interosseous membrane, both of which are the result of high activity levels. A prominent posterior pilaster divides the posterior tibia into two slopes, the shape of which could be the result of large *tibialis posterior* and *flexor digitorum longus*. The anteromedial side of the tibia has no muscle attachments and is only covered by fascia and skin. This portion of the tibia is usually convex or gently rounded. The first principal component, discussed above, describes the prominence and roundedness of the medial border, but the roundedness is affected by the angle of the posteromedial edge rather than its own intrinsic shape. Droplet-shaped tibiae would lack strong muscles in any direction, allowing the bone to curve convexly in all directions. In this scheme, the "muscular hypothesis", it is the muscles' shape and robustness that influence the bone's shape.

At this point, it is not possible to reconcile which hypothesis, the biomechanical or the muscular, has more influence. It is clear that neither acts singularly, and that some of the same factors influencing bone remodeling such as increased and repeated activity also influence muscle growth. As pointed out in Chapter 2, bones and muscles (and ligaments and tendons) do not remodel or grow at the same rate, so it is unclear which would have a greater influence at any given point in time. A suggested combined process, like the "accommodation hypothesis" argued by Lanyon (1980) and Carpenter and Carter (2008) may be that activity remodels bone into a shape that is better adapted to current axial stresses, while the increased muscle mass as a result of that activity limits bone growth in a particular direction. Perhaps the tibia, under anteroposterior stress, remodels into the diamond shape not only because of the direction of stress but because the lack of musculature at the anterior crest and posterior pilaster does not limit its growth in those directions; the ovoid may be similar. The half-moon and flat-side shapes could be a compromise, representing increased mediolateral and posterior bone growth, but limited on the lateral side by the mass of the *tibialis anterior* muscle belly.

The process most likely involves further hormonal controls, shown by the comparative studies of pubescent female athletes. Male tibiae are more robust than females both in this study and others in the literature. Although studies have shown estradiol has the greatest impact on lifelong bone health over other hormones, testosterone (which can be aromatised into estradiol) and other androgens present in higher concentrations in males have a clear benefit over estrogen in bone building, particularly during puberty (Clarke and Khosla 2009). The pubertal increase in androgens results in the sexual dimorphism seen in adult humans in bone density, bone mass, and muscle mass. As no current studies have compared male and female adolescent athletes in this aspect, it is unknown what effect exercise and activity have on the formation of bone shape, particularly as the activities practiced by ancient adolescents are unknown as well. The consistently higher musculoskeletal robusticity of males throughout the archaeological record, even in periods where females are also robust, combined with the results of modern studies of hormone therapy (Falahati-Nini *et al.* 2000; Frisco 2016), implies that higher levels of testosterone and other androgens result in greater musculoskeletal robusticity regardless of activity. Likewise, testosterone increases muscle growth. The implication of females' lower testosterone levels is that they will have smaller bones that may be less reactive to stress-induced remodeling because of slower osteocalcin production, and smaller muscles that do not load the periosteum as extensively as in males. Perhaps the droplet shape, with its convex edges and rounded angles, is the norm for females who additionally have a limited pubertal growth window.

Using these hypotheses of bone shape formation, it does appear that some of the shapes used in this study are biologically valid categories. They are significantly different in CSG properties and have varying levels of robusticity. The triangular shape appears to be the basic tibial cross-sectional shape, seen in controls from athletic studies and many individuals from the agricultural groups. The droplet shape is arguably a basic tibial shape seen in females, potentially the equivalent of the triangle with less surrounding muscle. The diamond and ovoid shapes can be interpreted as a compromise between periosteal pressure by the muscle bellies and axial stress on the bone, inducing remodeling, and the flat-side and half-moon can similarly be compromises between muscle pressure and mediolateral bending stress. It is possible that half-moon and flat-side are too similar to each other, conflating the results: the only difference is the convexity of the medial edge. Any time categories are assigned to biological specimens, there is bound to be some overlap; these include sex and age estimations and robusticity scores, all of which are used here. Biology does not fit neatly into scientifically-assigned categories. Perhaps the half-moon and flat-side categories, while distinct enough to identify successfully using inter-observer and intra-observer error tests, are only slight variations on the same general activity patterns and muscle growth and are subject to individual variation.

What insights can be gained into activity over the course of Sudanese history and prehistory from biomechanical and morphometric examinations of the tibia?

Despite these groups either coexisting or overlapping in time and geographic space, there is little evidence that the inhabitants of Jebel Moya were integrated into the Meroitic empire, and the focus of studies of the other groups has not been into subsistence; it was theorised that they were primarily agricultural based on their location and similar sites with evidence of agriculture. However, these data from tibial cross-sectional geometry and shape identifies them as similar to each other and to an English coastal-urban group and different from Jebel Moya. Thus it is clear that they were practicing differing methods of labour, including divisions of labour and types of habitual activity practiced. Although it is impossible to determine exactly what type of activity they performed, whether that is labour related to food production, athletics or leisure, or travel between grazing sites or fields, the general assumption that can be made from these data is that nomadic pastoralists were more active than agricultural groups as shown by TA and J values (Figures 8.2.2 and 8.2.9). This may be due to resource availability dependent on rain, political affiliations, or cultural preference, all of which deserve more archaeological investigation. The data from geometric morphometrics can be used in other studies of Sudanese bioarchaeology to identify more active and/or mobile groups and individuals.

Limitations of the dataset

There are weaknesses to this study that must be addressed. First, it was not possible to track change in activity and age-related change, as the individuals were dead and thus static. There were many individuals who could not be assigned to an age stage, possibly conflating the results. The research on the relationship between continued periosteal apposition and bone shape change in response to activity is unknown. Second, there is a lack of comparative research between males and females with regard to bone building. Many studies have attributed the lower robusticity and lower CSG values observed in archaeological females to sexual divisions of labour and activity, but future research into hormones and bone development, problematised here, could show differences that change the archaeological interpretation of female activity.

Another limitation was the use of the four CSG properties, total area, polar second moment of area, and second moments of area in two planes, used in order to compare results with recent studies. Section modulus, another CSG property representing strength, was not examined because not all studies consulted in the planning of the research used it. However, those that do find decreases in section modulus from hunting and gathering to agriculture as with TA and J (Ruff 2005; Nowlan *et al.* 2011). The second moment of area in the anteroposterior and mediolateral planes was not observed to strongly correlate with any other value, which is unusual here, and it is still unclear why. Additionally, the shape categories were defined using an older text and inter-observer testing; a grouping method such as cluster analysis could have been used, but failed in initial trials to produce repeatable results when tested.

Finally, while sedentism and agriculturalism were represented by three groups in this study, nomadic pastoralism was only represented by one. This was partly due to the lack of archaeological nomadic pastoralist cemeteries in this region, a result of the lack of research into continuing nomadism in general.

This study has shown significant differences between nomadic pastoralists and sedentary/agricultural groups, as predicted in the hypotheses in Chapter 5. The hypotheses also predicted differences between males and females which were also proven correct. High cross-sectional geometric values, high robusticity scores, and prevalence of tibiae showing anteroposterior loading seem to be indicative of nomadic pastoralism, at least in the Sudanese case, and lower cross-sectional geometric values, lower robusticity, and more tibiae showing mediolateral loading seem to be indicative of agriculture and sedentism in both Sudan and an outgroup. The possibility that females develop adult bone shape at a different rate than males must continue to be explored, as ethnographic accounts demonstrate a wide variety of labour and activity patterns worldwide. Additionally, the two hypotheses of bone shape development, the muscular and the biomechanical hypotheses, must continue to be researched to differentiate how much influence each has on development. The final chapter outlines the original goals and objectives of this project and details its major findings. It will suggest avenues for future research and suggestions for incorporating other archaeological and anthropological data into studies of biomechanical and morphometric analyses of the tibia.

10 Conclusion

The purpose of this research project was to investigate activity patterns in Sudan based on the difference in midshaft tibial cross-sectional shape between groups practicing differing subsistence strategies. Previous studies focused on other regions have observed changes in lower limb cross-sectional shape between time periods, with a focus on the transition to agriculture. However, human groups continued to practice pastoral and foraging-based lifestyles alongside agricultural communities, often within geographic areas examined together archaeologically; this is often due to variation in climate, available food sources, and political or cultural affiliations. The study presented here used ancient Sudan as a case study to investigate these differences between a nomadic-pastoral group and two sedentary agricultural groups using two methods: traditional cross-sectional geometric analysis, which indicates torsional strength, bending strength, and circularity, and geometric morphometrics, which allows for the quantification of shape difference through principal component analysis. The major findings of this study are as follows:

1. Tibiae from Jebel Moya, the pastoral site, are significantly longer than those from Gabati and 3-J-18, the agricultural sites. Cross-sectional geometric properties indicating compressive strength (TA) and torsional strength (J) are higher in the tibiae from Jebel Moya than those from Gabati and 3-J-18. Although values for females are lower than for males at all sites, females at Jebel Moya frequently had higher TA and J values than males at Gabati and 3-J-18, including when values were standardized for body mass. This indicates higher mobility for both sexes at Jebel Moya than at Gabati and 3-J-18. Cross-sectional geometric properties were similar between Gabati, 3-J-18, and Chichester, an outgroup from Britain; these three sites were significantly different from Jebel Moya, indicating that the difference in TA and J is due to lifestyle and activity rather than ethnic affiliation or genetics.

2. Shape categories for tibiae at midshaft, originally proposed by Hrdlička, were used in an updated form in this study. The diamond shape (Hrdlička’s rhomboid) was observed more frequently at Jebel Moya than at the agricultural sites. The ovoid shape was rarely observed

and was absent at Chichester. All sites have a high proportion of tibiae in the triangular category. The flat-side shape was observed in approximately 2:1 ratio with the half-moon category at all sites. The droplet shape was observed much more frequently for females; droplet and triangular were overrepresented for females.

3. Principal component analysis and comparison with previous studies were used to explore whether these shapes categories were biologically valid. In particular, the diamond shape is seen in groups where high mobility is expected, and the half-moon and flat-side shapes is seen in groups where mediolateral bending is expected. The high frequency of diamond-shaped tibiae at Jebel Moya indicates that at least some members of the group had high levels of mobility, which corroborates the relatively high TA and J values; the distribution of half-moon and flat-side shaped tibiae at the agricultural sites indicates the practice of activities with mediolateral rather than anteroposterior bending, potentially farming activities.

4. The droplet shape is currently unexplained in the relevant literature. A proposed explanation is that bone-building, which occurs at its most rapid pace during puberty, is strongly influenced by androgens, which also spur muscle growth. Females, lacking androgens, rarely gain as much bone mass or muscle mass as males. If tibial cross-sectional shape is influenced not only by axial stresses but also local pressure from muscle bellies, individuals lacking those muscle pressures against the tibia may continue to remodel in a more convex direction, resulting in the droplet shape. However, several females, particularly at Chichester and 3-J-18, were assigned to the triangular category, complicating this argument.

5. This study was unable to link individual shapes with any unique activities. The types of activity practiced by individuals in ancient societies were doubtless more varied than an analysis of this type can find, and an attempt to find divisions of labour based on tibial midshaft shape would not be successful: despite proposed differences based on productive labour, the tibia responds to bone modeling and remodeling stimuli from all activity, including inactivity, over a period of years during which activity patterns may change.

Tibial midshaft cross-sectional shape cannot be conclusively used to discriminate groups based on subsistence strategy, but it can be used to indicate relative levels of mobility, which in this case are higher in the nomadic pastoral group than in agricultural and sedentary groups.

It is proposed that these methods be used on a wider range of material. It is evident that there is a difference in shape varieties between the Sudanese nomadic-pastoral and agricultural groups, indicating differences in activity for this cultural context: the longitudinal change seen in many studies may be more complex than previously thought when pastoral groups are considered. The focus on the transition to agriculture within archaeology could be improved with the additional examination of pastoral groups, which are often overlooked. It is important to study a variety of nomadic and semi-nomadic groups worldwide to compare mobility, particularly as many studies track temporal change in tibial shape without consideration of the nomadic alternative. The use of geometric morphometrics could also improve studies of cross-sectional geometry by providing a more nuanced interpretation of shape, particularly regarding I_{max}/I_{min}, which does not appear sensitive enough to note differences between shapes that may have either activity-based or biological explanations. Further, bone building in females must be explored further; as many studies –including this study - note less significant differences between females than males, it is possible the difference is biological rather than activity-based as ethnographic studies show varying workloads for females worldwide. For Sudanese archaeology, there are implications for how these groups are examined. In addition to the cultural-affiliation and ecological differences, researchers must seek to investigate differences in activity practices using cultural material. As the tibial morphology indicates that some males at Jebel Moya were highly mobile than others, perhaps there are unique patterns of social behavior and hierarchy that could be revealed through artifacts. The differences between Jebel Moya and the two agricultural sites indicates a diversity of practice and mobility within Meroitic and Medieval Sudan that has been suggested by cultural material but needed further examination. The distinction in tibial morphology is clear, and can now be used to advance arguments on the nature of archaeological nomadic-pastoral and agricultural behavior and labour practices.

References

Ackerman, K.E. and Misra, M. (2011). Bone health and the female athlete triad in adolescent athletes. *The Physician and sportsmedicine*, 39(1), pp.131–141.

Adams, J.M. (1997). Global land environments during the last 130,000 years. *Oak Ridge National Laboratory*. Available at: http://www.esd.ornl.gov/projects/qen/nerc.html [Accessed January 25, 2016].

Adams, R.M., Lamberg-Karlovsky, C.C. and Moran, W.L. (1974). The Mesopotamian Social Landscape: A View from the Frontier. *Bulletin of the American Schools of Oriental Research. Supplementary Studies*, 20: Recons, pp.1–20.

Addison, F. (1949). *Jebel Moya, Vol I: Text*. London: Oxford University Press.

Agarwal, S. and Glencross, B.C. (2011). *Social Bioarchaeology*. John Wiley & Sons.

Agur, A.M., Ng-Thow-Hing, V., Ball, K.A., Fiume, E. and McKee, N.H. (2003). Documentation and three-dimensional modelling of human soleus muscle architecture. *Clinical Anatomy*, 16(4), pp.285–293.

Ali-Khan, S.E., Krakowski, T., Tahir, R. and Daar, A.S. (2011). The use of race, ethnicity and ancestry in human genetic research. *The HUGO journal*, 5(1-4), pp.47–63.

Amprino, R. (1985). The influence of stress and strain in the early development of shaft bones. An experimental study on the chick embryo tibia. *Anatomy and embryology*, 172(1), pp.49–60.

Andermann, S. (1976). The cnemic index: a critique. *American Journal of Physical Anthropology*, 44(2), pp.369–373.

Antich, T.J. and Brewster, C.E. (1985). Osgood-Schlatter Disease: Review of Literature and Physical Therapy Management. *The Journal of Orthopaedic and Sports Physical Therapy*, 7(1), pp.5–10.

Appadurai, A. (1986). *The social life of things : commodities in cultural perspective / edited by Arjun Appadurai*. Cambridge : Cambridge University Press.

Arabi, A., Nabulsi, M., Maalouf, J., Choucair, M., Khalifé, H., Vieth, R. and El-Hajj Fuleihan, G. (2004). Bone mineral density by age, gender, pubertal stages, and socioeconomic status in healthy Lebanese children and adolescents. *Bone*, 35(5), pp.1169–1179.

Arisaka, O., Arisaka, M., Nakayama, Y., Fujiwara, S. and Yabuta, K. (1995). Effect of testosterone on bone density and bone metabolism in adolescent male hypogonadism. *Metabolism: Clinical and Experimental*, 44(4), pp.419–423.

Aristotle (2004). J.A.K. Thompson, *trans. The Nicomachean Ethics*. London: Penguin.

Aristotle (2015). Francis Ferguson, *trans. Politics*. Oxford: Aeterna.

Ascadi, G. and Nemeskeri, J. (1970). *History of human lifespan and mortality*. Budapest: Akademiai Kiado.

Asouti, E. and Fuller, D.Q. (2013). A Contextual Approach to the Emergence of Agriculture in Southwest Asia. *Current anthropology*, 54(3), pp.299–345.

Attarian, D.E., McCrackin, H.J., Devito, D., McElhaney, J.H. and Garrett, W.E. (1985). Biomechanical characteristics of human ankle ligaments. *Orthopaedic Transactions*, 9(3), pp.553–554.

Auerbach, B.M. and Ruff, C.B. (2004). Human body mass estimation: a comparison of “morphometric” and “mechanical” methods. *American Journal of Physical*

Anthropology, 125(4), pp.331–342.

Auerbach, B.M. and Ruff, C.B. (2006). Limb bone bilateral asymmetry: variability and commonality among modern humans. *Journal of Human Evolution*, 50(2), pp.203–218.

Bailey, R. (2014). World Football's 20 Best 2-Footed Players Right Now. *Bleacher Report*. Available at: http://bleacherreport.com/articles/2029362-world-footballs-20-best-two-footed-players-right-now [Accessed April 9, 2015].

Barak, M.M., Lieberman, D.E. and Hublin, J.-J. (2011). A Wolff in sheep's clothing: trabecular bone adaptation in response to changes in joint loading orientation. *Bone*, 49(6), pp.1141–1151.

Bass, W.M. (2004). *Human Osteology: A Laboratory and Field Manual*. 5th ed. Columbia, MO: Missouri Archaeological Society.

BBC (2011). TV viewing time "underestimated." *BBC Arts & Entertainment*. Available at: http://www.bbc.co.uk/news/entertainment-arts-12651728 [Accessed April 9, 2015].

Beaumont, R. (2012). An Introduction to Principal Component Analysis & Factor Analysis. Available at: www.floppybunny.org/robin/web/virtualclassroom/stats/statistics2/**pca**1.pdf [Accessed January 18, 2015].

Bergman, A.G., Fredericson, M., Ho, C. and Matheson, G.O. (2004). Asymptomatic tibial stress reactions: MRI detection and clinical follow-up in distance runners. *American Journal of Roentgenology*, 183(3), pp.635–638.

Bianchi, R.S. (2004). *Daily Life of the Nubians*. Westport, CT: Greenwood Publishing Group.

Binford, L. (1980). Willow smoke and dogs' tails: Hunter-gatherer settlement systems and archaeological site formation. *American Antiquity*, 45, pp.4–20.

Binford, L.R. (1971). Mortuary Practices: Their Study and Their Potential. *Memoirs of the Society for American Archaeology*, 25, pp.6–29.

Blair, S.N., Cheng, Y. and Holder, J.S. (2001). Is physical activity or physical fitness more important in defining health benefits? *Medicine and Science in Sports and Exercise*, 33(6 Suppl), pp.S379–99; discussion S419.

Blench, R. and MacDonald, K. (2006). *The Origins and Development of African Livestock: Archaeology, Genetics, Linguistics and Ethnography*. R. Blench & K. MacDonald, eds. London: Routledge.

Bocquet-Appel, J.-P. and Masset, C. (1982). Farewell to Paleodemography. *Journal of Human Evolution*, 11, pp.321–333.

Bonhomme, V., Picq, S., Gaucherel, C. and Claude, J. (2014). Momocs: Outline Analysis using R. *Journal of Statistical Software*, 56(13).

Bookstein, F.L. (1997). Landmark methods for forms without landmarks: morphometrics of group differences in outline shape. *Medical Image Analysis*, 1(3), pp.225–243.

Bookstein, F.L. (1986). Size and Shape Spaces for Landmark Data in Two Dimensions. *Statistical Science*, 1(2), pp.181–242.

Boot, A.M., de Ridder, M.A., Pols, H.A., Krenning, E.P. and de Muinck Keizer-Schrama, S.M. (1997). Bone mineral density in children and adolescents: relation to puberty, calcium intake, and physical activity. *The Journal of Clinical Endocrinology and Metabolism*, 82(1), pp.57–62.

Borgognini Tarli, S.M. and Repetto, E. (1986). Methodological considerations on the study of sexual dimorphism in past human populations. *Human Evolution*, 1(1), pp.51–66.

Boulle, E.-L. (2001a). Evolution of Two Human Skeletal Markers of the Squatting Position: A Diachronic Study From Antiquity to the Modern Age. *American Journal of Physical Anthropology*, 115, pp.50–56.

Boulle, E.-L. (2001b). Osteological features associated with ankle hyperdorsiflexion. *International Journal of Osteoarchaeology*, 11(5), pp.345–349.

Brace, C.L., Seguchi, N., Quintyn, C.B., Fox, S.C., Nelson, A.R., Manolis, S.K. and Qifeng, P. (2006). The questionable contribution of the Neolithic and the Bronze Age to European craniofacial form. *Proceedings of the National Academy of Sciences of the United States of America*, 103(1), pp.242–247.

Bradley, R.J. (1992). *Nomads in the Archaeological Record: Meroitica 13*. Berlin: Akademie Verlag.

Bradney, M., Pearce, G., Naughton, G., Sullivan, C., Bass, S., Beck, T., Carlson, J. and Seeman, E. (1998). Moderate exercise during growth in prepubertal boys: changes in bone mass, size, volumetric density, and bone strength: a controlled prospective study. *Journal of Bone and Mineral Research*, 13(12), pp.1814–1821.

Brass, M. (2001). Tracing the Origins of the Ancient Egyptian Cattle Cult. *Azania: Archaeological Research in Africa*, pp. 1–7.

Brass, M. (2009). Towards an archaeology of social organisation at Jebel Moya , 5th – 1st millennium BC. *Sudan & Nubia: the Sudan Archaeological Research …*, (Plate 1), pp.120–125.

Brass, M. (2013). Revisiting a hoary chestnut: the nature of early cattle domestication in North-East Africa. *Sahara (Segrate, Italy)*, 24, pp.65–70.

Brass, M. (2014). The southern frontier of the Meroitic State : The view from Jebel Moya. *African Archaeological Review*.

Brass, M. (2015). Interactions and Pastoralism Along the Southern and Southeastern Frontiers of the Meroitic State, Sudan. *Journal of world prehistory*, 28(4), pp.255–288.

Brass, M. and Schwenniger, J.-L. (2013). Jebel Moya (Sudan): new dates from a mortuary complex at the southern Meroitic frontier. *Azania*, 48(4), pp.455–472.

Brickley, M. and McKinley, J.I. (2004). Guidelines to the Standards for Recording Human Remains. *BABAO/IFA*.

Broca, P. (1868). On the crania and bones of Les Eyzies, or the ancient cave-men of Perigord. *Anthropological Review*, 6, pp.408–411.

Broca, P. (1880). *Mémoires sur les ossements des Eyzies (Epoque du Mammouth)*. Paris: Reinwald.

Brown, N.M. (1994). Exploring Space Shape. *Penn State News*. Available at: http://news.psu.edu/story/141490/1994/03/01/research/exploring-space-shape [Accessed April 2, 2015].

Brown, T.A. and Brown, K. (2011). *Biomolecular Archaeology: An Introduction*. revised. Chichester: John Wiley & Sons.

Buikstra, J. and Ubelaker, D. (1994). Standards for data collection from human skeletal remains. *Archaeological Survey Research Series*, 44.

Burr, D.B., Milgrom, C., Fyhrie, D., Forwood, M., Nyska, M., Finestone, A., Hoshaw, S., Saiag, E. and Simkin, A. (1996). In vivo measurement of human tibial strains during vigorous activity. *Bone*, 18(5), pp.405–410.

Busk, G. (1869). On the caves of Gibraltar in which human remains and works of art have been found. In *Transactions of the International Congress of Prehistoric Archaeology, 3rd Session*. International Congress of Prehistoric Archaeology. London: Spottiswoode & Co.

Butzer, K.W. (1975). *Early hydraulic civilization in Egypt: a study in cultural ecology*. Chicago: University of Chicago Press.

Buxton, L.H. (1938). Platymeria and platycnemia. *Journal of Anatomy*, 73(Pt 1), pp.31–36.

Buzon, M.R. (2006). Biological and Ethnic Identity in New Kingdom Nubia. *Current anthropology*, 47(4), pp.683–695.

Buzon, M.R. and Bowen, G.J. (2010). Oxygen and carbon isotope analysis of human tooth enamel from the new kingdom site of tombos in nubia. *Archaeometry*, 52(5), pp.855–868.

Byrd, B. (1994). Public and private, domestic and corporate: the emergence of the southwest Asian village. *American Antiquity*, 59(4), pp.639–666.

Cameron, J. (1934). *The Skeleton of British Neolithic Man: Including a Comparison with that of Other Prehistoric Periods and More Modern Times*.

Carpenter, R.D. and Carter, D.R. (2008). The mechanobiological effects of periosteal surface loads. *Biomechanics and Modeling in Mechanobiology*, 7(3), pp.227–242.

Carr, C. (1995). Mortuary practices: Their social, philosophical-religious, circumstantial, and physical determinants. *Journal of Archaeological Method and Theory*, 2(2), pp.105–200.

Carrier, D.R., Chase, K. and Lark, K.G. (2005). Genetics of canid skeletal variation: size and shape of the pelvis. *Genome Research*, 15(12), pp.1825–1830.

Carroll, S.C. (1988). Wrestling in Ancient Nubia. *Journal of sport history*, 15(2), pp.121–137.

Cavalli-Sforza, L.L. (1996). The Spread of Agriculture and Nomadic Pastoralism. In D. Harris, ed. *The Origins and Spread of Agriculture in Eurasia*. London: UCL Press, pp. 51–69.

Chaix, L. (2011). A review of the history of cattle in the Sudan throughout the Holocene. In H. Jousse & J. Lessur, eds. *People and animals in Holocene Africa: Recent advances in archaeozoology*. Reports in African Archaeology . Berlin, pp. 13–26.

Chaix, L. and Grant, A. (1993). Palaeoenvironment and economy at Kerma, Northern Sudan, during the third millennium BC: archaeozoological and botanical evidence. In L. Krzyzaniak, M. Kobusiewicz, & J. Alexander, eds. *Environmental change and human culture in the Nile Basin and Northern Africa until the second millennium BC*. Poznan, Poland: Archaeological Museum, pp. 399–404.

Chang, C. and Koster, H.A. (1986). Beyond Bones: Toward an Archaeology of Pastoralism. *Advances in Archaeological Method and Theory*, 9, pp.97–148.

Chen, H.-N., Yang, K., Dong, Q.-R. and Wang, Y. (2014). Assessment of tibial rotation and meniscal movement using kinematic magnetic resonance imaging. *Journal of Orthopaedic Surgery and Research*, 9, p.65.

Chen, Y.-J., Scher, I. and Powers, C.M. (2010). Quantification of Patellofemoral Joint Reaction Force During Functional Activities. *Journal of Applied Biomechanics*, 26, pp.415–423.

Christodoulou, A., Terzidis, I., Natsis, K., Gigis, I. and Pournaras, J. (2004). Soleus accessorius, an anomalous muscle in a young athlete: case report and analysis of the literature. *British Journal of Sports Medicine*, 38(6), p.e38.

Churchill, S.E. and Morris, A.G. (1998). Muscle marking morphology and labour intensity in prehistoric Khoisan foragers. *International Journal of Osteoarchaeology*, 8(5), pp.390–411.

City Centre Partnership Chichester City Centre Map.

Claasen, C.P. (1991). Gender, Shellfishing, and the Shell Mound Archaic. In Joan M. Gero & Margaret W. Conkey, ed. *Engendering Archaeology: Women and Prehistory*. Oxford: Basil Blackwell, pp. 276–300.

Clarke, B.L. and Khosla, S. (2009). Androgens and bone. *Steroids*, 74(3), pp.296–305.

Clutton-Brock, J. (2000). Cattle, sheep, and goast south of the Sahara: an archaeozoological perspective. In R. Blench & K. C. MacDonald, eds. *The Origins and Development of African Livestock: Archaeology, Genetics, Linguistics, and Enthnography*. London: UCL Press.

Collins, F.S. (2004). What we do and don’t know about “race”, “ethnicity”, genetics and health at the dawn of the genome era. *Nature Genetics*, 36(11 Suppl), pp.S13–5.

Collipal, E., Vargas, R., Parra, X., Silva, H. and del Sol, M. (2007). Diaphyseal Nutrient Foramina in the Femur, Tibia and Fibula Bones. *International Journal of Morphology,* 25(2).

Conard, N.J. and Lehner, M. (2001). The 1988/1989 Excavation of Petrie’s “Workmen’s Barracks” at Giza. *Journal of the American Research Council in Egypt*, 38, pp.21–60.

Conkey, M.W. and Spector, J.D. (1984). Archaeology and the Study of Gender. *Advances in Archaeological Method and Theory*, 7, pp.1–38.

Cooper, D.M.L., Ahamed, Y., Macdonald, H.M. and McKay, H.A. (2008). Characterising cortical density in the mid-tibia: intra-individual variation in adolescent girls and boys. *British Journal of Sports Medicine*, 42(8), pp.690–695.

Coppolillo, P. (2000). The Landscape Ecology of Pastoral Herding: Spatial Analysis of Land Use and Livestock Production in East Africa. *Human Ecology*, 28(4), pp.527–560.

Cordain, L., Miller, J.B., Eaton, S.B., Mann, N., Holt, S.H. and Speth, J.D. (2000). Plant-animal subsistence ratios and macronutrient energy estimations in worldwide hunter-gatherer diets. *The American Journal of Clinical Nutrition*, 71(3), pp.682–692.

Cowin, S.C. (2001). The false premis in Wolff’s law. In S. C. Cowin, ed. *Bone Biomechanics Handbook*. Boca Raton: CRC Press, pp. 301–325.

Crabtree, P. (2007). Women, Gender, and Pastoralism. In S. M. Nelson, ed. *Identity and Subsistence: Gender Strategies for Archaeology*. Lanham, MD: AltaMira, pp. 237–258.

Cribb, R. (1991). *Nomads in archaeology*. Cambridge: Cambridge University Press.

Currey, J.D. (2002). *Bones: Structure and Mechanics*. Princeton: Princeton University Press.

Currey, J.D. (1984). *The Mechanical Adaptations of Bones*. Princeton: Princeton University Press.

Dahab, A.H. (1995). *Nubia & Sails And Nile Valley Civilizatin [sic]*. Aswan: Lehnert and Landrock.

Dauber, W. and Feneis, H. (2007). *Pocket atlas of human anatomy*. 5th rev. Stuttgart: Thieme.

Davies, T.G., Shaw, C.N. and Stock, J.T. (2012). A test of a new method and software for the rapid estimation of cross-sectional geometric properties of long bone diaphyses from 3D laser surface scans. *Archaeological and Anthropological Sciences*.

Dawkins, W.B. (1880). *Early Man in Britain*. London: MacMillan.

Dawkins, W.B. and Busk, G. (1870). On the discovery of platycnemic men in Denbighshire. *Journal of the Ethnological Society of London*, 2(4), pp.440–468.

Debets, G.F. (1948). *Paleoanthropology of the USSR*. Moscow-Leningrad: USSR Academy of Sciences.

Delgado-Calle, J., Garmilla, P. and Riancho, J.A. (2012). Do epigenetic marks govern bone mass and homeostasis? *Current Genomics*, 13(3), pp.252–263.

Deng, H.-W., Xu, F.-H., Davies, K.M., Heaney, R. and Recker, R.R. (2002). Differences in bone mineral density, bone mineral content, and bone areal size in fracturing and non-fracturing women, and their interrelationships at the spine and hip. *Journal of Bone and Mineral Metabolism*, 20(6), pp.358–366.

Devlin, M.J., Stetter, C.M., Lin, H.M., Beck, T.J., Legro, R.S., Petit, M.A., Lieberman, D.E. and Lloyd, T. (2010). Peripubertal estrogen levels and physical activity affect femur geometry in young adult women. *Osteoporosis International*, 21(4), pp.609–617.

Dittmar, M. (2002). Functional and postural lateral preferences in humans: interrelations and life-span age differences. *Human Biology; An International Record of Research*, 74(4), pp.569–585.

Dove, E., Burrell, C., Ohman, J.C. and Irish, J.D. (2015). A (w)hole new idea: Using nutrient foramen location to identify relative growth and the center of ossification in juvenile tibiae. In *AAPA*. 84th American Association of Physical Anthropologists. St Louis.

Drake, R., Vogl, A.W. and Mitchell, A.W. (2010). *Gray's Anatomy for Students*. 2nd ed. Philadelphia: Churchill Livingstone.

Drapeau, M.S.M. and Streeter, M.A. (2006). Modeling and remodeling responses to normal loading in the human lower limb. *American Journal of Physical Anthropology*, 129(3), pp.403–409.

Dwek, J.R. (2010). The periosteum: what is it, where is it, and what mimics it in its absence? *Skeletal Radiology*, 39(4), pp.319–323.

Edwards, D.N. (1998). *Gabati: A Meroitic, Post-Meroitic and Medieval Cemetery in Central Sudan*. London: The Sudan Archaeological Research Society.

Edwards, D.N. (2001). The Christianisation of Nubia: some archaeological pointers. *Sudan & Nubia : the Sudan Archaeological Research Society bulletin*, 5.

Edwards, D.N. (2004). *The Nubian Past: An Archaeology of the Sudan*. London: Routledge.

Edwards, D.N. (2007). The Archaeology of Sudan & Nubia. *Annual Review of Anthropology*, 36, pp.211–228.

Ekenman, I., Tsai-Felländer, L., Johansson, C. and O'Brien, M. (1995). The plantar flexor muscle attachments on the tibia. A cadaver study. *Scandinavian Journal of Medicine & Science in Sports*, 5(3), pp.160–164.

Elewa, A.M.T. (2010). *Morphometrics for nonmorphometricians*. Berlin: Springer.

Endo, B. and Kimura, T. (1970). Postcranial Skeleton of the Amud Man. In H. Suzuki & F. Takai, eds. *The Amud Man and His Cave Site*. Tokyo: University of Tokyo, pp. 231–406.

Enghoff, I.B. (1986). Freshwater Fishing from a Sea-Coast Settlement: The Ertebolle Locus Revisited. *Journal of Danish Archaeology*, 5(1), pp.62–76.

Epstein, D. (2013). *The Sports Gene: Inside the Science of Extraordinary Athletic Performance*. New York: Current.

Evans-Pritchard, E.E. (1940). *The Nuer: A Description of the Modes of Livelihood and Political Institutions of a Nilotic People*. Oxford: Clarendon.

Falahati-Nini, A., Riggs, B.L., Atkinson, E.J., O'Fallon, W.M., Eastell, R. and Khosla, S. (2000). Relative contributions of testosterone and estrogen in regulating bone resorption and formation in normal elderly men. *The Journal of Clinical Investigation*, 106(12), pp.1553–1560.

Fazlollah, A.E., Auerbach, B.M. and Shaw, C.N. (2014). Effects of the relative position of the fibula on the cross-sectional properties of the tibia. In *AAPA*. 84th American Association of Physical Anthropologists.

Fazlollah, A.E., Auerbach, B.M. and Shaw, C.N. (2015). Positional relationship of the fibula to cross-sectional geometric properties of the tibia as compared in different sporting groups. In *AAPA*. 85th American Association of Physical Anthropologists.

Fernandez-Gimenez, M.E. and Le Febre, S. (2006). Mobility in pastoral systems: Dynamic flux or downward trend? *International Journal of Sustainable Development & World Ecology*, 13(5), pp.341–362.

Field, A. (2013). *Discovering Statistics Using IBM SPSS Statistics*. SAGE.

Forel, B., Gabillot, M., Monna, F., Forel, S., Dommergues, C.H., Gerber, S., Petit, C., Mordant, C. and Chateau, C. (2009). Morphometry of Middle Bronze Age palstaves by Discrete Cosine Transform. *Journal of archaeological science*, 36(3), pp.721–729.

Fowler, N.E., Rodacki, A.L.F. and Rodacki, C.D. (2006). Changes in stature and spine kinematics during a loaded walking task. *Gait & Posture*, 23(2), pp.133–141.

Fratkin, E.M., Roth, E.A. and Nathan, M.A. (1999). When Nomads Settle: The Effects of Commoditization, Nutritional Change, and Formal Education of Ariaal and Rendille Pastoralists. *Current Anthropology*, 40(5), pp.729–735.

Freeman, M.A.R. and Pinskerova, V. (2005). The movement of the normal tibio-femoral joint. *Journal of Biomechanics*, 38(2), pp.197–208.

Frisco, D.J. (2016). What is Osteoporosis? *Spine-Health.com*. Available at: http://www.spine-health.com/conditions/osteoporosis/what-osteoporosis [Accessed March 9, 2016].

Frost, H.M. (1997). On our age-related bone loss: insights from a new paradigm. *Journal of Bone and Mineral Research*, 12(10), pp.1539–1546.

Frost, H.M. (1969). Tetracycline-based histological analysis of bone remodeling. *Calcified Tissue Research*, 3(1), pp.211–237.

Fujimura, R., Ashizawa, N., Watanabe, M., Mukai, N., Amagai, H., Fukubayashi, T., Hayashi, K., Tokuyama, K. and Suzuki, M. (1997). Effect of resistance exercise training on bone formation and resorption in young male subjects assessed by biomarkers of bone metabolism. *Journal of Bone and Mineral Research*, 12(4), pp.656–662.

Fukunaga, T., Kawakami, Y., Kubo, K. and Kanehisa, H. (2002). Muscle and Tendon Interaction During Human Movements. *Exercise & Sport Sciences Reviews*, 30(3), pp.106–110.

Fuller, D.Q. (2004). Early Kushite Agriculture: Archaeobotanical Evidence from Kawa. *Sudan & Nubia : the Sudan Archaeological Research Society Bulletin*, 8, pp.70–74.

Fuller, D.Q. (2004). Islands in the Nile: investigations at the Fourth Cataract in Sudanese Nubia. *Archaeology International*, 8.

Fuller, D.Q. (2013). Agricultural Innovation and State Collapse in Meroitic Nubia. In *Archaeology of African Plant Use*.

Fuller, D.Q. and Edwards, D.N. (2001). Medieval Plant Economy in Middle Nubia: Preliminary Archaeobotanical Evidence from Nauri. *Sudan & Nubia: the Sudan Archaeological Research Society Bulletin*, 5.

Gabbard, C. and Hart, S. (1996). A question of foot dominance. *The Journal of General Psychology*, 123(4), pp.289–296.

Gallais, J. (1984). *Hommes du Sahel*. Paris: Flammarion.

Gerharz, R.G. (1994). *Jebel Moya: Meroitica 14*. Berlin: Akademie Verlag.

Gilchrist, R. (1999). *Gender and archaeology : contesting the past / Roberta Gilchrist*. London : Routledge.

Gillette, J.C., Stevermer, C.A., Meardon, S.A., Derrick, T.R. and Schwab, C.V. (2009). Upper extremity and lower back moments during carrying tasks in farm children. *Journal of applied biomechanics*, 25(2), pp.149–155.

Gilsanz, V., Chalfant, J., Kalkwarf, H., Zemel, B., Lappe, J., Oberfield, S., Shepherd, J., Wren, T. and Winer, K. (2011). Age at onset of puberty predicts bone mass in young adulthood. *The Journal of Pediatrics*, 158(1), pp.100–5, 105.e1.

Ginns, A. (2006). Preliminary Report on the Excavations Conducted on Mis Island (AKSC), 2005-2006. *Sudan & Nubia*, 10, pp.13–19.

Ginns, A. (2010a). 3-J-18 The Church (Draft report). *Sudan & Nubia*, (June).

Ginns, A. (2010b). The cemetery associated with the church at 3-J-18 (Draft). *Sudan & Nubia*.

Ginter, J.K. (2011). Using a Bioarchaeological Approach to Explore Subsistence Strategies. In R. Pinhasi & J. T. Stock, eds. *p, li { white-space: pre-wrap; }Human Bioarchaeology of the Transition to Agriculture*. Chichester: John Wiley & Sons, pp. 107–149.

Goldstein, R.E., Warren, P.B. and Ball, R.C. (2012). Shape of a ponytail and the statistical physics of hair fiber bundles. *Physical Review Letters*, 108(7), p.078101.

Gould, S.J. and Lewontin, R.C. (1979). The Spandrels of San Marco and the Panglossian Paradigm: A Critique of the Adaptationist Programme. *Proceedings of the Royal Society B: Biological Sciences*, 205(1161), pp.581–598.

Gray, H. (1901). *Gray's Anatomy (Facsimile edition, 2003)*. Ann Arbor, MI: JW Edwards.

Grimston, S.K., Willows, N.D. and Hanley, D.A. (1993). Mechanical loading regime and its relationship to bone mineral density in children. *Medicine and Science in Sports and Exercise*, 25(11), pp.1203–1210.

Haaland, R. (1997). Emergence of sedentism: new ways of living, new ways of symbolizing. *Antiquity*, 71(272), pp.374–385.

Haapasalo, H., Kannus, P., Sievänen, H., Pasanen, M., Uusi-Rasi, K., Heinonen, A., Oja, P. and Vuori, I. (1998). Effect of long-term unilateral activity on bone mineral density of female junior tennis players. *Journal of Bone and Mineral Research*, 13(2), pp.310–319.

Hackner, S. (2013). “Platycnemia” in two Nubian populations: an explanation of shape change in the tibial diaphysis. In *Egyptian Bioarchaeology Conference*. Egyptian Bioarchaeology Conference.

Hackner, S. and Antoine, D. (2016). Cross-sectional geometry vs traditional indices: What can we gain from these recording methods? In *AAPA*. 85th American Association of Physical Anthropologists.

Hall, S.J. (2012). *Basic Biomechanics*. 6th ed. New York: McGraw-Hill.

Handsman, R.G. (1991). Whose Art Was Found at Lepinski Vir? In J. M. Gero & M. W. Conkey, eds. *Engendering Archaeology: Women and Prehistory*. Oxford: Basil Blackwell, pp. 329–365.

Harlan, J.R. (1989). Wild-grass seed harvesting in the Sahara and Sub-Sahara of Africa. In *Foraging and Farming: The Evolution of Plant Exploitation*. London: Unwin Hyman, pp. 79–95.

Hart, D., Doherty, A., Le Hegarat, K., Sibun, L. and Russell, J. (2012). A Post-Excavation Assessment And Updated Project Design For Excavations At Eastgate Square, Chichester, West Sussex (Draft).

Harvati, K. and Weaver, T.D. (2006). Human cranial anatomy and the differential preservation of population history and climate signatures. *The Anatomical Record. Part A, Discoveries in Molecular, Cellular, and Evolutionary Biology*, 288(12), pp.1225–1233.

Hatcher, L. (1994). Principal Component Analysis: A Step-By-Step Approach to Using the SAS System for Factor Analysis and Structural Equation Modeling.

Hawkey, D.E. and Merbs, C.F. (1995). Activity-induced Musculoskeletal Stress Markers (MSM) and Subsistence Strategy Changes among Ancient Hudson Bay Eskimos. *International Journal of Osteoarchaeology*, 5(September 1994), pp.324–338.

Heaney, R.P. (2003). Bone mineral content, not bone mineral density, is the correct bone measure for growth studies. *American Journal of Clinical Nutrition*, 78(2), pp.350–351.

Henderson, C.Y., Mariotti, V., Pany-Kucera, D., Lopreno, G.P., Villotte, S. and Wilczak, C. (2012). The effect of age on entheseal changes at some fibrocartilaginous entheses. In *AAPA*. 82nd American Association of Physical Anthropologists.

Henderson, C.Y., Mariotti, V., Pany-Kucera, D., Villotte, S. and Wilczak, C. (2013). Recording specific entheseal changes of fibrocartilaginous entheses: initial tests using the coimbra method. *International Journal of Osteoarchaeology,* 23(2), pp.152–162.

Henderson, C.Y., Mariotti, V., Pany-Kucera, D., Villotte, S. and Wilczak, C. (2016). The new “coimbra method”: A biologically appropriate method for recording specific features of fibrocartilaginous entheseal changes. *International Journal of Osteoarchaeology*, 26(5), pp.925–932.

Hert, J., Sklenská, A. and Lisková, M. (1971). Reaction of bone to mechanical stimuli. 5. Effect of intermittent stress on the rabbit tibia after resection of the peripheral nerves. *Folia Morphologica*, 19(4), pp.378–387.

Herzmark, M.H. (1938). The Evolution of the Knee Joint. *American Journal of Bone and Joint Surgery*, 1, pp.77–84.

Hildebrand, M. and Goslow, G. (2001). *Analysis of Vertebrate Structure*. 5th ed. New York: Wiley.

Hoagland, T.M. (2015). Ankle Joint Anatomy. *MedScape*. Available at: http://www.emedicine.medscape.com/article/1946201-overview [Accessed April 6, 2016].

Ingold, T. (1996). Growing Plants and Raising Animals. In D. Harris, ed. *The Origins and Spread of Agriculture and Pastoralism in Eurasia*. London: UCL Press.

Inskip, S., Palmer, J. and Schats, R. (2016). Diachronic Analysis of “Squatting Facets” in Rural and Urban Dutch populations. In *Working Your Fingers to the Bone: An Interdisciplinary Conference on Identifying Occupation from the Skeleton*. Coimbra, Portugal.

Irish, J.D. (2006). Who were the ancient Egyptians? Dental affinities among Neolithic through postdynastic peoples. *American Journal of Physical Anthropology*, 129(4), pp.529–543.

Irish, J.D. and Konigsberg, L. (2007). The ancient inhabitants of Jebel Moya redux: measures of population affinity based on dental morphology. *International Journal of Osteoarchaeology*, 17(2), pp.138–156.

Irons, W. (1975). *The Yomut Turkmen: A study of spatial organization among a central Asian Turkic-speaking population*. Ann Arbor, MI: Museum of Anthropology, University of Michigan 58.

Isman, R.E. and Inman, V.T. (1969). Anthropometric studies of the human foot and ankle. *Bulletin of Prosthetic Research*, 11, pp.97–129.

Jackson, T.L. (1991). Pounding Acorn: Women’s Production as Social and Economic Focus. In J. M. Gero & M. W. Conkey, eds. *Engendering Archaeology: Women and Prehistory*. Oxford: Basil Blackwell, pp. 301–328.

Jend, H., Ney, R. and Heller, M. (1985). Evaluation of Tibiofibular Motion Under Load Conditions by Computed Tomography. *Journal of Orthopaedic Research*, 3, pp.418–423.

Johal, P., Williams, A., Wragg, P., Hunt, D. and Gedroyc, W. (2005). Tibio-femoral movement in the living knee. A study of weight bearing and non-weight bearing knee kinematics using “interventional” MRI. *Journal of Biomechanics*, 38(2), pp.269–276.

Johnson, A.L. (2002). Cross-Cultural Analysis of Pastoral Adaptations and Organizational States: A Preliminary Study. *Cross-Cultural Research*, 36(2), pp.151–180.

Johnson, M. (2010). *Archaeological Theory: An Introduction*. 2nd ed. Oxford: Blackwell.

Johnson, M.A., Polgar, J., Weightman, D. and Appleton, D. (1973). Data on the distribution of fibre types in thirty-six human muscles. An autopsy study. *Journal of the Neurological Sciences*, 18(1), pp.111–129.

Jones, D.A. (2015). *Ritual and religion in the Ohlone cultural area of Central California*. Master thesis.

Judd, M. (2004). Gabati: Health in Transition. *Sudan & Nubia*, 8, pp.84–89.Judd, M. (2012). *Gabati: A Meroitic, Post-Meroitic and Medieval Cemetery in Central Sudan. Vol II: The Physical Anthropology*. London: The Sudan Archaeological Research Society.

Jurmain, R., Cardoso, F.A., Henderson, C. and Villotte, S. (2011). Bioarchaeology's Holy Grail: The Reconstruction of Activity. In A. L. Grauer, ed. *A Companion to Paleopathology*. Oxford, UK: Wiley-Blackwell, pp. 531–552.

Kelly, R.L. (1995). *The foraging spectrum: Diversity in hunter-gatherer lifeways*. Washington: Smithsonian Institution Press.

Kendall, T. (1997). *Kerma and the Kingdom of Kush, 2500-1500 B.C.: The Archaeological Discovery of an Ancient Nubian Empire*. Washington, DC: National Museum of African Art, Smithsonian Institution.

Khan, K., McKay, H.A., Haapasalo, H., Bennell, K.L., Forwood, M.R., Kannus, P. and Wark, J.D. (2000). Does childhood and adolescence provide a unique opportunity for exercise to strengthen the skeleton? *Journal of Science and Medicine in Sport*, 3(2), pp.150–164.

Khazanov, A.M. (1994). *Nomads and the Outside World*. 2nd ed. Madison, WI: University of Wisconsin Press.

Kiebzak, G.M. (1991). Age-related bone changes. *Experimental Gerontology*, 26(2-3), pp.171–187.

Kirshner, S., Courseault, J. and Authement, A. (2015). Knee Joint Anatomy: Overview, Gross Anatomy, Natural Variants. *Medscape E-medicine*. Available at: http://emedicine.medscape.com/article/1898986 [Accessed August 30, 2016].

Kirwan, L. (2002). Nubia: An African Frontier Zone. In T. Hägg, L. Török, & D. A. Welsby, eds. *Studies on the History of Late Antique and Christian Nubia*. Bury St Edmunds: Variorum, pp. 330–337.

Kitaoka, K., Furman, B. and Saha, S. (1998). Periosteum: Its Biomechanical Role in Bone Fracture. In *North American Congress on Biomechanics*. North American Congress on Biomechanics. Waterloo, Ontario.

Kizilkanat, E., Boyan, N., Ozsahin, E.T., Soames, R. and Oguz, O. (2007). Location, number and clinical significance of nutrient foramina in human long bones. *Annals of anatomy / Anatomischer Anzeiger: Official Organ of the Anatomische Gesellschaft*, 189(1), pp.87–95.

Kroeber, C. (1962). *Two papers on the aboriginal ethnography of California*. Dept. of Anthropology: University of California.

Kujala, U.M., Kaprio, J., Kannus, P., Sarna, S. and Koskenvuo, M. (2000). Physical activity and osteoporotic hip fracture risk in men. *Archives of Internal Medicine*, 160(5), pp.705–708.

Kuzminsky, S.C. and Gardiner, M.S. (2012). Three-dimensional laser scanning: potential uses for museum conservation and scientific research. *Journal of archaeological science*, 39(8), pp.2744–2751.

Laerd Statistics (2013). One-way ANOVA - How to report the significance results, homogeneity of variance and running post-hoc tests. *Laerd Statistics*. Available at: https://statistics.laerd.com/statistical-guides/one-way-anova-statistical-guide-

4.php [Accessed October 31, 2016].

Lahr, M.M. (1996). *The evolution of modern human diversity: a study of cranial variation*. Cambridge: Cambridge University Press.

Landry, S.C., McKean, K.A., Hubley-Kozey, C.L., Stanish, W.D. and Deluzio, K.J. (2007). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *The American Journal of Sports Medicine*, 35(11), pp.1888–1900.

Lane, P.J. (1994). The temporal structuring of settlement space among the Dogon of Mali: an ethnoarchaeological study. *Architecture and order: approaches to social space*, pp.196–216.

Lanyon, L.E., Hampson, W.G.J., Goodship, A.E. and Shah, J.S. (1975). Bone Deformation Recorded in vivo from Strain Gauges Attached to the Human Tibial Shaft. *Acta orthopaedica Scandinavica*, 46(2), pp.256–268.

Lanyon, L.E. (1980). The influence of function on the development of bone curvature. An experimental study on the rat tibia. *Journal of zoology*, 192(4), pp.457–466.

Lanyon, L.E. (1987). Functional strain in bone tissue as an objective, and controlling stimulus for adaptive bone remodelling. *Journal of Biomechanics*, 20(11-12), pp.1083–1093.

Lanyon, L.E., Hampson, W.G.J., Goodship, A.E. and Shah, J.S. (1975). Bone Deformation Recorded in vivo from Strain Gauges Attached to the Human Tibial Shaft. *Acta Orthopaedica Scandinavica*, 46(2), pp.256–268.

Lapauw, B., Taes, Y., Simoens, S., Van Caenegem, E., Weyers, S., Goemaere, S., Toye, K., Kaufman, J.-M. and T'Sjoen, G.G. (2008). Body composition, volumetric and areal bone parameters in male-to-female transsexual persons. *Bone*, 43(6), pp.1016–1021.

Larsen, C.S. (1995). Biological Changes in Human Populations with Agriculture. *Annual Review of Anthropology*, 24(1), pp.185–213.

Larsen, C.S. (2003). Equality for the sexes in human evolution? Early hominid sexual dimorphism and implications for mating systems and social behavior. *Proceedings of the National Academy of Sciences of the United States of America*, 100(16), pp.9103–9104.

Larsen, C.S. (2015). *Bioarchaeology: Interpreting Behavior from the Human Skeleton*. Cambridge: Cambridge University Press.

Latimer, B., Ohman, J.C. and Lovejoy, C.O. (1987). Talocrural joint in African hominoids: implications for Australopithecus afarensis. *American Journal of Physical Anthropology*, 74(2), pp.155–175.

Latta, L.L. (1979). *The Mechanical Function of the Interosseous Membrane in the Leg of Man*. Doctoral dissertation. University of Miami.

Lazenby, R.A. (1990a). Continuing periosteal apposition. I: Documentation, hypotheses, and interpretation. *American Journal of Physical Anthropology*, 82(4), pp.451–472.

Lazenby, R.A. (1990b). Continuing periosteal apposition. II: The significance of peak bone mass, strain equilibrium, and age-related activity differentials for mechanical compensation in human tubular bones. *American Journal of Physical Anthropology*, 82(4), pp.473–484.

Leach, H.M. (2003). Human Domestication Reconsidered. *Current anthropology*, 44(3), pp.349–368.

Leblanc, A. and Schneider, V. (1992). Countermeasures against space flight relatedbone loss. *Acta Astronautica*, 27, pp.89–92.

Ledger, M., Holtzhausen, L.M., Constant, D. and Morris, A.G. (2000). Biomechanical beam analysis of long bones from a late 18th century slave cemetery in Cape Town, South Africa. *American Journal of Physical Anthropology*, 112(2), pp.207–216.

Lee, R.B. (1968). What Hunters Do for a Living, or, How to Make Out on Scarce Resources. In Richard B. Lee, ed. *Man the Hunter*. New York: Aldine Publishing Company, pp. 30–48.

Lee, R.B. (1979). *The !Kung San: Men, Women, and Work in a Foraging Society*. Cambridge: Cambridge University Press.

Lees, S.H. and Bates, D.G. (1974). The Origins of Specialized Nomadic Pastoralism: A Systemic Model. *American antiquity*, 39(2).Leblanc, A. and Schneider, V. (1991). Can the adult skeleton recover lost bone? *Experimental Gerontology*, 26, pp.189–201.

Lesko, L.H. (1994). *Pharaoh's workers: The villagers of Deir el Medina*. Ithaca: Cornell University Press.

Lieberman, D.E., Pearson, O.M., Polk, J.D., Demes, B. and Crompton, A.W. (2003). Optimization of bone growth and remodeling in response to loading in tapered mammalian limbs. *The Journal of Experimental Biology*, 206(Pt 18), pp.3125–3138.

Lieberman, D.E., Polk, J.D. and Demes, B. (2004). Predicting long bone loading from cross-sectional geometry. *American Journal of Physical Anthropology*, 123(2), pp.156–171.

Lieverse, A.R., Stock, J.T., Katzenberg, M.A. and Haverkort, C.M. (2011). The Bioarchaeology of Habitual Activity and Dietary Change in the Siberian Middle Holocene. In R. Pinhasi & J. T. Stock, eds. *Human Bioarchaeology of the Transition to Agriculture*. Chichester, UK: John Wiley & Sons, Ltd, pp. 263–291.

Lindholm, C., Hagenfeldt, K. and Ringertz, B.M. (1994). Pubertal development in elite juvenile gymnasts. Effects of physical training. *Acta Obstetricia et Gynecologica Scandinavica*, 73(3), pp.269–273.

Lindholm, C., Hagenfeldt, K. and Ringertz, H. (1995). Bone mineral content of young female former gymnasts. *Acta Paediatrica*, 84, pp.1109–1112.

Little, M.A. (2001). Lessons Learned from the South Turkana Ecosystem Project. In *Human Ecology Special Issue No. 10*. pp. 137–149.

Lloyd, A.B. (2014). *Ancient Egypt: State and Society*. 2nd ed. New York: Oxford University Press.

Lorentzon, M., Swanson, C., Andersson, N., Mellström, D. and Ohlsson, C. (2005). Free testosterone is a positive, whereas free estradiol is a negative, predictor of cortical bone size in young Swedish men: the GOOD study. *Journal of Bone and Mineral Research*, 20(8), pp.1334–1341.

Lovejoy, C.O. (2007). The natural history of human gait and posture. Part 3. The knee. *Gait & Posture*, 25(3), pp.325–341.

Lovejoy, C.O., Burstein, A.H. and Heiple, K.G. (1976). The biomechanical analysis of bone strength: a method and its application to platycnemia. *American Journal of*

Physical Anthropology, 44(3), pp.489–505.

Lovejoy, C.O., Meindl, R.S., Pryzbeck, T.R. and Mensforth, R.P. (1985). Chronological metamorphosis of the auricular surface of the ilium: a new method for the determination of adult skeletal age at death. *American Journal of Physical Anthropology*, 68(1), pp.15–28.

Lovell, N. (1994). Biological Differentiation at Predynastic Naqada, Egypt: An Analysis of Dental Morphological Traits. *American Journal of Physical Anthropology*, 93, pp.427–433.

Lowerston, J. and Myerscough, J. (1977). *Time to Spare in Victorian England*. Rossendale, UK: Revival Books.

Lucas, P. (2007). Charles Darwin, “little Dawkins” and the platycnemic Yale men: introducing abioarchaeological tale of the descent of man. *Archives of Natural History*, 34(2), pp.318–345.

MacDonald, R.M. (1999). *In the teeth of the problem: dental anthropology and the reconstruction of Africa dietary regimes*. Doctoral dissertation. UCL.

Macintosh, A.A., Davies, T.G., Ryan, T.M., Shaw, C.N. and Stock, J.T. (2013). Periosteal versus true cross-sectional geometry: a comparison along humeral, femoral, and tibial diaphyses. *American Journal of Physical Anthropology*, 150(3), pp.442–452.

Macintosh, A.A., Pinhasi, R. and Stock, J.T. (2014). Lower limb skeletal biomechanics track long-term decline in mobility across ~6150 years of agriculture in Central Europe. *Journal of archaeological science*, 52, pp.376–390.

Macintosh, A.A., Davies, T.G., Pinhasi, R. and Stock, J.T. (2015). Declining tibial curvature parallels ~6150 years of decreasing mobility in Central European agriculturalists. *American Journal of Physical Anthropology*, 157(2), pp.260–275.

MacLeod, N. (2016a). Identifying Sexual Dimorphism in Wolf (Canis lupus) Skulls via the Direct Biometric Analysis of Digital Images. In *MORPH16*.

MacLeod, N. (2016b). Morphometrics Overview.

Maher, P.J. and Ilgen, J.S. (2013). Osgood-Schlatter disease. *BMJ case reports*, 2013.

Marchi, D. (2007). Relative strength of the tibia and fibula and locomotor behavior in hominoids. *Journal of Human Evolution*, 53(6), pp.647–655.

Marchi, D. (2008). Relationships between lower limb cross-sectional geometry and mobility: the case of a Neolithic sample from Italy. *American Journal of Physical Anthropology*, 137(2), pp.188–200.

Marchi, D., Sparacello, V. and Shaw, C. (2011). Mobility and Lower Limb Robusticity of a Pastoralist Neolithic Population from. In R. Pinhasi & J. T. Stock, eds. *Bioarchaeology and the Transition to Agriculture*. Chichester: John Wiley & Sons, pp. 317–346.

Margulies, J.Y., Simkin, A., Leichter, I., Bivas, A., Steinberg, R., Giladi, M., Stein, M., Kashtan, H. and Milgrom, C. (1986). Effect of intense physical activity on the bone-mineral content in the lower limbs of young adults. *The Journal of Bone and Joint Surgery. American Volume*, 68(7), pp.1090–1093.

Marshall, W.A. and Tanner, J.M. (1969). Variations in pattern of pubertal changes in girls. *Archives of Disease in Childhood*, 44(235), pp.291–303.

Martin, R. (1914). *Lehrbuch der Anthropologie: in systematischer darstellung mit besonderer berüksichtigung der anthropolgischen methoden für studierende ästze und forschungsreisende*. Stuttgart: Gustav Fischer Verlag.

Marx, K. and Engels, F. (2014). *Capital: A Critique of Political Economy, Volume 2 - Primary Source Edition, Volume 2*. BiblioLife.

Mayo Clinic Staff (2011). Mayo Clinic. Diseases and Conditions: Osgood-Schlatter's Disease. Available at: http://www.mayoclinic.com/health/osgood-schlatter-disease [Accessed August 20, 2011].

Mays, S. (1998). *The Archaeology Of Human Bones*. London: Routledge.

Mays, S. (1999). A Biomechanical Study of Activity Patterns in a Medieval Human Skeletal Assemblage. *International Journal of Osteoarchaeology*, 73, pp.68–73.

Mays, S. (2016). Bone-formers and bone-losers in an archaeological population. *American Journal of Physical Anthropology*, 159(4), pp.577–584.

Mazess, R.B. and Whedon, G.D. (1983). Immobilization and Bone. *Calcified Tissue International*, 35(3), pp.265–267.

McCartney, G. and Hepper, P. (1999). Development of lateralized behaviour in the human fetus from 12 to 27 weeks' gestation. *Developmental Medicine and Child Neurology*, 41(2), pp.83–86.

McCorkle, C. (1987). Punas, pastures, and fields: Grazing strategies and the agropastoral dialectic in an indigenous Andean community. In D. L. Browman, ed. *Arid Land Use Strategies and Risk Management in the Andes.* Boulder, CO: Westview Press, pp. 57–70.

McCorriston, J., Harrower, M., Martin, L. and Oches, E. (2012). Cattle Cults of the Arabian Neolithic and Early Territorial Societies. *American anthropologist*, 114(1), pp.45–63.

McGuire, R. (1983). Breaking down cultural complexity: Inequality and heterogeneity. In M. Schiffer, ed. *Advances in archaeological method and theory*. New York: Academic Press, pp. 91–142.

McIntosh, R.J. (2005). *Ancient Middle Niger: Urbanism and the Self-Organizing Landscape*. Cambridge: Cambridge University Press.

McKown, T. and Keith, A. (1939). *The Stone Age of Mt. Carmel, Vol. 2, The Fossil Remains from the Levalloiso-Mousterian*. Oxford: Clarendon.

McLean, D.D., Hurd, A.R. and Rogers, N.B. (2004). *Kraus' Recreation and Leisure in Modern Society*. 7th ed. Boston: Jones & Bartlett.

McLeod, K.J., Rubin, C.T., Otter, M.W. and Qin, Y.X. (1998). Skeletal cell stresses and bone adaptation. *The American Journal of the Medical Sciences*, 316(3), pp.176–183.

McMillan, M. (2014). *Biomechanical exposures and work-related musculoskeletal disorders among Saskatchewan farmers*. Master thesis. Queen's University, Ontario.

Ménassa, L. and Laferrière, P. (1974). *La sâqia: technique et vocabulaire de la roue à eau égyptienne*. Cairo: Institut français d'archéologie orientale du Caire.

Menkes, A., Mazel, S., Redmond, R.A., Koffler, K., Libanati, C.R., Gundberg, C.M., Zizic, T.M., Hagberg, J.M., Pratley, R.E. and Hurley, B.F. (1993). Strength training increases regional bone mineral density and bone remodeling in middle-aged and older men. *Journal of Applied Physiology*, 74(5), pp.2478–2484.

Milgrom, C., Finestone, A., Levi, Y., Simkin, A., Ekenman, I., Mendelson, S., Millgram, M., Nyska, M., Benjuya, N. and Burr, D. (2000). Do high impact exercises produce higher tibial strains than running? *British Journal of Sports Medicine*, 34(3), pp.195–199.

Milnor, J. (2010a). Geometry of Growth and Form: Commentary on D'Arcy Thompson. Princeton Institute of Advanced Study. Available at: https://video.ias.edu/milnor-80th [Accessed March 10, 2016]

Milnor, J. (2010b). The Geometry of Growth and Form. Princeton Institute of Advanced Study. Available at: https://www.ias.edu/ideas/2010/milnor-geometry-of-growth [Accessed March 10, 2016]

Minns, R.J., Bremble, G.R. and Campbell, J. (1975). The geometrical properties of the human tibia. *Journal of Biomechanics*, 8(3-4), pp.253–255.

Mølgaard, C., Thomsen, B.L. and Michaelsen, K.F. (1998). Influence of weight, age and puberty on bone size and bone mineral content in healthy children and adolescents. *Acta Paediatrica*, 87(5), pp.494–499.

Molleson, T. (1994). The eloquent bones of Abu Hureyra. *Scientific American*, 271(2), pp.70–75.

Molleson, T. (2000). The Human Remains. In A. M. T. Moore, ed. *Village on the Euphrates. From Foraging to Farming at Abu Hureyra*. Oxford: Oxford University Press, pp. 533–544.

Molleson, T., Jones, K. and Jones, S. (1993). Dietary change and the effects of food preparation on microwear patterns in the Late Neolithic of abu Hureyra, northern Syria. *Journal of Human Evolution*, 24(6), pp.455–468.

Molleson, T. and Rosas, A. (2012). Origins of the Neolithic people of Abu Hureyra, northern Syria: An attempt to address an archaeological question through a study of the mandibles. *Bioarchaeology of the Near East*, 6, pp.3–20.

Moritz, M. (2013). Livestock Transfers, Risk Management, and Human Careers in a West African Pastoral System. *Human Ecology*, 41(2), pp.205–219.

Morris, A.G. (1986). Long Bone Flattening Paper Abstract & Data. (unpublished), pp.1–5.

Morseth, B., Emaus, N. and Jørgensen, L. (2011). Physical activity and bone: The importance of the various mechanical stimuli for bone mineral density. A review. *Norsk Epidemiologi*, 20(2).

Moustafa, A., Sugiyama, T., Saxon, L.K., Zaman, G., Sunters, A., Armstrong, V.J., Javaheri, B., Lanyon, L.E. and Price, J.S. (2009). The mouse fibula as a suitable bone for the study of functional adaptation to mechanical loading. *Bone*, 44(5), pp.930–935.

Mukherjee, R., Rao, C.R. and Trevor, J.C. (1955). *The Ancient Inhabitants of Jebel Moya (Sudan)*. Cambridge: Cambridge University Press.

Mundy, G.R. (1999). *Bone Remodeling and Its Disorders*. 2nd ed. London: Martin Dunitz.

Murray, S.S., Schoeninger, M.J., Bunn, H.T., Pickering, T.R. and Marlett, J.A. (2001). Nutritional Composition of Some Wild Plant Foods and Honey Used by Hadza Foragers of Tanzania. *Journal of Food Composition and Analysis*, 14(1), pp.3–13.

Nagurka, M.L. and Hayes, W.C. (1980). Technical Notes: An Interactive Graphics Package for Calculating Cross-Sectional Properties of Complex Shapes. *Journal* *of Biomechanics*, 13(59-64).

Nelson, S.M. (2007). *Identity and subsistence: Gender strategies for archaeology*. Lanham, MD: Rowman & Littlefield Publishers.

Netter, F.H. (2006). *Atlas of Human Anatomy*, 4th ed. Philadelphia, PA: Elsevier.

Nigg, B.M., MacIntosh, B.R. and Mester, J. (2000). *Biomechanics and biology of movement*. Champaign, Ill: Human Kinetics.

Nikander, R., Kannus, P., Rantalainen, T., Uusi-Rasi, K., Heinonen, A. and Sievänen, H. (2010). Cross-sectional geometry of weight-bearing tibia in female athletes subjected to different exercise loadings. *Osteoporosis International*, 21(10), pp.1687–1694.

Nikander, R., Sievänen, H., Heinonen, A., Karstila, T. and Kannus, P. (2008). Load-specific differences in the structure of femoral neck and tibia between world-class moguls skiers and slalom skiers. *Scandinavian Journal of Medicine & Science in Sports*, 18(2), pp.145–153.

Nikita, E., Siew, Y.Y., Stock, J., Mattingly, D. and Lahr, M.M. (2011). Activity patterns in the Sahara Desert: an interpretation based on cross-sectional geometric properties. *American Journal of Physical Anthropology*, 146(3), pp.423–434.

Van Noordewijk, M. (1984). *Ecology Textbook for the Sudan*. 1st ed. Khartoum: Khartoum Unviersity Press.

Nordström, P., Pettersson, U. and Lorentzon, R. (1998). Type of physical activity, muscle strength, and pubertal stage as determinants of bone mineral density and bone area in adolescent boys. *Journal of Bone and Mineral Research*, 13(7), pp.1141–1148.

Nowlan, N.C., Jepsen, K.J. and Morgan, E.F. (2011). Smaller, weaker, and less stiff bones evolve from changes in subsistence strategy. *Osteoporosis International*, 22(6), pp.1967–1980.

Ogilvie-Harris, D.J., Reed, S.C. and Hedman, T.P. (1994). Disruption of the ankle syndesmosis: biomechanical study of the ligamentous restraints. *Arthroscopy*, 10(5), pp.558–560.

O'Neill, M.C. and Ruff, C.B. (2004). Estimating human long bone cross-sectional geometric properties: a comparison of noninvasive methods. *Journal of Human Evolution*, 47(4), pp.221–235.

Oyewole, O.O., Akinpelu, A.O. and Odole, A.C. (2013). Development of the tibiofemoral angle in a cohort of Nigerian children during the first 3 years of life. *Journal of Children's Orthopaedics*, 7(2), pp.167–173.

Oygucu, I.H., Kurt, M.A., Ikiz, I., Erem, T. and Davies, D.C. (1998). Squatting facets on the neck of the talus and extensions of the trochlear surface of the talus in late Byzantine males. *Journal of Anatomy*, 192 (Pt 2), pp.287–291.

Paasuke, M. (2011). Biomechanics of the knee joint. Available at: http://seltsft.eu/wp-content/uploads/2011/06/Mati_Pa%CC%88a%CC%88suke_po%CC%83lveliigese_biomehaanika.pdf [Accessed May 4, 2016]

Papathanasiou, A. (2011). Health, Diet and Social Implications in Neolithic Greece from the Study of Human Osteological Material. In R. Pinhasi & J. T. Stock, eds. *Human Bioarchaeology of the Transition to Agriculture*. Chichester, UK: John Wiley & Sons, Ltd, pp. 87–106.

Pearson, O.M. (2000). Activity, Climate, and Postcranial Robusticity: implication for modern Human Origins and Scenarios of adaptive change. *Current Anthropology*, 41(4), pp.569–607.

Pearson, O.M. and Lieberman, D.E. (2004). The aging of Wolff's "law": ontogeny and responses to mechanical loading in cortical bone. *American Journal of Physical Anthropology*, Suppl 39, pp.63–99.

Pellegrini, A., Teschler-Nicola, M., Bookstein, F. and Mitteroecker, P. (2011). Craniofacial morphology in Austrian Early Bronze Age populations reflects sex-specific migration patterns. *Journal of anthropological sciences = Rivista di antropologia : JASS / Istituto italiano di antropologia*, 89, pp.139–151.

Percy, E.C. and Telep, G.N. (1984). Anomalous muscle in the leg: soleus accessorium. *The American Journal of Sports Medicine*, 12(6), pp.447–450.

Perreard Lopreno, G. (2016). Bone geometry & strength: anthropological and medical approaches to assess the influence of occupational activities on the skeleton. In *Working Your Fingers to the Bone: An Interdisciplinary Conference on Identifying Occupation from the Skeleton*. Coimbra, Portugal.

Perry, E.M. (2004). *Bioarchaeology of labor and gender in the prehispanic American Southwest*. Doctoral dissertation. University of Arizona.

Peters, J. and von den Driesch, A. (1993). Mesolithic fishing at the junction of the Nile and Atbara, Central Sudan. In *Skeletons in Her Cupboard*. pp. 75–83.

Petrie, W.M.F. (1896). *Naqada and Ballas*. Warminster: Aris & Phillips.

Pettitt, P. and White, M. (2012). *The British Palaeolithic: Hominin Societies at the Edge of the Pleistocene World*. London: Routledge.

Phenice, T.W. (1969). A newly developed visual method of sexing the os pubis. *American Journal of Physical Anthropology*, 30(2), pp.297–301.

Polly, P.D. (2012). Geometric morphometrics: an introduction. Available at: http://www.indiana.edu/~g562/Lectures/Lecture 1 - Introduction to Geometric Morphometrics.pdf [Accessed April 2, 2015].

Pomeroy, E. and Zakrzewski, S.R. (2009). Sexual Dimorphism in Diaphyseal Cross-sectional Shape in the Medieval Muslim Population of Ecija, Spain, and Anglo-Saxon Great Chesterford, UK. *International Journal of Osteoarchaeology*, 65, pp.50–65.

Pontzer, H., Raichlen, D.A., Wood, B.M., Mabulla, A.Z.P., Racette, S.B. and Marlowe, F.W. (2012). Hunter-gatherer energetics and human obesity. *PLOS One*, 7(7), pp.1-8.

Porcic, M. (2008). Nomadic Pastoralism in the Early Bronze Age of the Central Balkans: Evaluation of Background Knowledge. *Balcanica*, (34), pp.7–31.

Porcic, M. and Stefanovic, S. (2009). Physical activity and social status in Early Bronze Age society: The Mokrin necropolis. *Journal of Anthropological Archaeology*, 28(3), pp.259–273.

Prakasam, G., Yeh, J.K., Chen, M.M., Castro-Magana, M., Liang, C.T. and Aloia, J.F. (1999). Effects of growth hormone and testosterone on cortical bone formation and bone density in aged orchiectomized rats. *Bone*, 24(5), pp.491–497.

Price, T.D. and Gebauer, A.B. (1995). *Last hunters, first farmers: New perspectives on the prehistoric transition to agriculture*. 1st ed. Santa Fe, N.M: School of American Research Press.

Qin, Y.X., Rubin, C.T. and McLeod, K.J. (1998). Nonlinear dependence of loading intensity and cycle number in the maintenance of bone mass and morphology.

Journal of Orthopaedic Research, 16(4), pp.482–489.

Raichlen, D.A., Wood, B.M., Gordon, A.D., Mabulla, A.Z.P., Marlowe, F.W. and Pontzer, H. (2014). Evidence of Levy walk foraging patterns in human hunter-gatherers. *Proceedings of the National Academy of Sciences of the United States of America*, 111(2), pp.728–733.

Rando, C. (2016). The Human Remains Collections at the UCL Institute of Archaeology: Recent Acquisitions from Eastgate Square, Chichester, Sussex. *Archaeology International*, 19, pp.79–83.

Reilly, D.T. and Martens, M. (1972). Experimental analysis of the quadriceps muscle force and patello-femoral joint reaction force for various activities. *Acta orthopaedica Scandinavica*, 43(2), pp.126–137.

Relethford, J.H. (2004). Boas and beyond: migration and craniometric variation. *American Journal of Human Biology*, 16(4), pp.379–386.

Renaud, S., Auffray, J.-C. and la Porte, S. de (2010). Epigenetic effects on the mouse mandible: common features and discrepancies in remodeling due to muscular dystrophy and response to food consistency. *BMC Evolutionary Biology*, 10, p.28.

Rhodes, J.A. and Knüsel, C.J. (2005). Activity-related skeletal change in medieval humeri: cross-sectional and architectural alterations. *American Journal of Physical Anthropology*, 128(3), pp.536–546.

Richter, J. and Noe-Nygaard, N. (2003). A late mesolithic hunting station at Agernaes, Fyn, Denmark. Differentiation and specialization in the late Ertebolle culture, heralding the introduction of agriculture? *Acta Archaeologica*, 74(1), pp.1–64.

Robb, J.E. (1998). The interpretation of skeletal muscle sites: a statistical approach. *International Journal of Osteoarchaeology*, 8, pp.363–377.

Robb, J.E., Bigazzi, R., Lazzarini, L., Scarsini, C. and Sonego, F. (2001). Social “status” and biological “status”: a comparison of grave goods and skeletal indicators from Pontecagnano. *American Journal of Physical Anthropology*, 115(3), pp.213–222.

Roberts, C.A., Lee, F. and Bintliff, J. (1989). *Burial Archaeology: Current research, methods and developments*. C. A. Roberts, F. Lee, & J. Bintliff, eds. Oxford: BAR.

Rogers, J., Shepstone, L. and Dieppe, P. (1997). Bone formers: osteophyte and enthesophyte formation are positively associated. *Annals of the Rheumatic Diseases*, 56(2), pp.85–90.

Rogers, J. and Waldron, T. (2001). DISH and the monastic way of life. *International Journal of Osteoarchaeology*, 11(5), pp.357–365.

Rojek, C. (1985). *Capitalism and Leisure Theory*. London: Tavistock.

Rojek, C. (2013). Is Marx still relevant to the study of leisure? *Leisure Studies*, 32(1), pp.19–33.

Rojek, C., Shaw, S.M. and Veal, A.J. (2006). *A Handbook of Leisure Studies*. C. Rojek, S. M. Shaw, & A. J. Veal, eds. London: Palgrave Macmillan UK.

Rosen, C.J., Glowacki, J. and Bilezikian, J.P. (1999). *The Aging Skeleton*. San Diego: Academic Press.

Rose, P. and Smith, L.M.V. (1998). The Meroitic Pottery. In D. N. Edwards, ed. *Gabati: A Meroitic, Post-Meroitic and Medieval Cemetery in Central Sudan*. London: The Sudan Archaeological Research Society.

Rubin, C.T. and McLeod, K.J. (1994). Promotion of bony ingrowth by frequency-specific, low-amplitude mechanical strain. *Clinical Orthopaedics and Related Research*, (298), pp.165–174.

Ruff, C.B. (1987). Sexual dimorphism in human lower limb bone structure: relationship to subsistence strategy and sexual division of labor. *Journal of Human Evolution*, 16, pp.391–416

Ruff, C.B. (2008). Femoral/humeral strength in early African Homo erectus. *Journal of Human Evolution*, 54(3), pp.383–390.

Ruff, C.B. (2000). Body size, body shape, and long bone strength in modern humans. *Journal of Human Evolution*, 38(2), pp.269–290.

Ruff, C.B. (2005). Mechanical determinants of bone form: insights from skeletal remains. *Journal of Musculoskeletal & Neuronal Interactions*, 5(3), pp.202–212.Ruff, C.B. (2008). Biomechanical Analyses of Archaeological Human Skeletons. In M. A. Katzenberg & S. R. Saunders, eds. *Biological Anthropology of the Human Skeleton*. Hoboken, NJ, USA: John Wiley & Sons, Inc., pp. 183–206.

Ruff, C.B. and Hayes, W.C. (1983a). Cross-sectional geometry of Pecos Pueblo femora and tibiae--a biomechanical investigation: II. Sex, age, side differences. *American Journal of Physical Anthropology*, 60(3), pp.383–400.

Ruff, C.B. and Hayes, W.C. (1983b). Cross-sectional geometry of Pecos Pueblo femora and tibiae--a biomechanical investigation: I. Method and general patterns of variation. *American Journal of Physical Anthropology*, 60(3), pp.359–381.

Ruff, C.B., Holt, B. and Trinkaus, E. (2006). Who's afraid of the big bad Wolff?: "Wolff's law" and bone functional adaptation. *American Journal of Physical Anthropology*, 129(4), pp.484–498.

Ruff, C.B. and Jones, H.H. (1981). Bilateral asymmetry in cortical bone of the humerus and tibia-sex and age factors. *Human Biology*, 53(1), pp.69–86.

Ruff, C.B. and Larsen, C.S. (2014). Long Bone Structural Analyses and the Reconstruction of Past Mobility: A Historical Review. In K. J. Carlson & D. Marchi, eds. *Reconstructing Mobility: Environmental, Behavioral, and Morphological Determinants*. New York: Springer, pp. 13–30.

Ruff, C.B., Larsen, C.S. and Hayes, W.C. (1984). Structural changes in the femur with the transition to agriculture on the Georgia coast. *American Journal of Physical Anthropology*, 64(2), pp.125–136.

Runestad, J.Q., Ruff, C.B., Nieh, J.C., Thorington, R.W. and Teaford, M.F. (1993). Radiographic estimation of long bone cross-sectional geometric properties. *American Journal of Physical Anthropology*, 90(2), pp.207–213.

Ryan, T.M. and Shaw, C.N. (2015). Gracility of the modern Homo sapiens skeleton is the result of decreased biomechanical loading. *Proceedings of the National Academy of Sciences of the United States of America*, 112(2), pp.372–377.

Sadoghi, P., Borbas, P., Friesenbichler, J., Scheipl, S., Kastner, N., Eberl, R., Leithner, A. and Gruber, G. (2012). Evaluating the tibial and femoral insertion site of the anterior cruciate ligament using an objective coordinate system: a cadaver study. *Injury*, 43(10), pp.1771–1775.

Sadr, K. (1991). *The Development of Nomadism in Ancient Northeast Africa*. Philadelphia: University of Pennsylvania Press.

Sadr, K. (2008). Invisible herders? The archaeology of Khoekhoe pastoralists. *Southern African Humanities*, 20, pp.179–203.

Salem, G.J., Zernicke, R.F., Martinez, D.A. and Vailas, A.C. (1993). Adaptations of immature trabecular bone to moderate exercise: geometrical, biochemical, and biomechanical correlates. *Bone*, 14(4), pp.647–654.

Sallis, J.F. and Saelens, B.E. (2000). Assessment of physical activity by self-report: status, limitations, and future directions. *Research quarterly for exercise and sport*, 71(2 Suppl), pp.S1–14.

Sarringhaus, L.A., Stock, J.T., Marchant, L.F. and McGrew, W.C. (2005). Bilateral asymmetry in the limb bones of the chimpanzee (Pan troglodytes). *American Journal of Physical Anthropology*, 128(4), pp.840–845.

Scheuer, L. and Black, S.M. (2000). *Developmental Juvenile Osteology*. San Diego, CA: Academic Press.

Schleip, R. and Klingler, W. (2010). The fascial network: an exploration of its load bearing capacity and its potential role as a pain generator. In A. Vleeming, ed. *Proceedings of the 7th Interdisciplinary World Congress on Low Back & Pelvic Pain*. 7th Interdisciplinary World Congress on Low Back & Pelvic Pain. Los Angeles, CA.

Schleip, R. and Müller, D.G. (2013). Training principles for fascial connective tissues: scientific foundation and suggested practical applications. *Journal of Bodywork and Movement Therapies*, 17(1), pp.103–115.

Schultz, A.H. (1923). Fetal growth in man. *American Journal of Physical Anthropology*, 6(4), pp.389–399.

Schultz, A.H. (1926). Fetal Growth of Man and Other Primates. *The Quarterly Review of Biology*, 1(4), pp.465–521.

Scurr, J.C., White, J.L. and Hedger, W. (2010). The effect of breast support on the kinematics of the breast during the running gait cycle. *Journal of Sports Sciences*, 28(10), pp.1103–1109.

Shaw, C.N. and Stock, J.T. (2009). Intensity, repetitiveness, and directionality of habitual adolescent mobility patterns influence the tibial diaphysis morphology of athletes. *American Journal of Physical Anthropology*, 140(1), pp.149–159.

Shaw, C.N. and Stock, J.T. (2011). The influence of body proportions on femoral and tibial midshaft shape in hunter-gatherers. *American Journal of Physical Anthropology*, 144(1), pp.22–29.

Shaw, C.N. and Stock, J.T. (2013). Extreme mobility in the Late Pleistocene? Comparing limb biomechanics among fossil Homo, varsity athletes and Holocene foragers. *Journal of Human Evolution*, 64(4), pp.242–249.

Shaw, I. (2000). *The Oxford History of Ancient Egypt*. Oxford: Oxford University Press.

Shefelbine, S.J., Tardieu, C. and Carter, D.R. (2002). Development of the femoral bicondylar angle in hominid bipedalism. *Bone*, 30(5), pp.765–770.

Sherratt, A.G. (1983). The secondary products revolution of animals in the Old World. *World Archaeology*, 15, pp.90–104.

Sherwood, R.J. and Duren, D.L. (2013). Growth of a species, an association, a science: 80 years of growth and development research. *American Journal of Physical Anthropology*, 150(1), pp.1–4.

Shinnie, P.L. (1996). *Ancient Nubia*. Khartoum: Sudan Antiquities Service.

Singh, I. (1959). Squatting Facets on the Talus and Tibia in Indians. *Journal of Anatomy*, 93, pp.540–550.

Slice, D.E., Bookstein, F.L., Marcus, L.F. and Rohlf, F.J. (2007). A Glossary for Geometric Morphometrics. *Imagine*. Available at: http://life.bio.sunysb.edu/morph/glossary/gloss1.html [Accessed April 2, 2015].

Sofaer Derevenski, J.R. (2000). Sex differences in activity-related osseous change in the spine and the gendered division of labor at Ensay and Wharram Percy, UK. *American Journal of Physical Anthropology*, 111(3), pp.333–354.

Soler, A. (2012). *Life and Death in a Medieval Nubian Farming Community: The Experience at Mis Island*. Doctoral dissertation. University of Michigan.

Sommer, M. (2007). *Bones and Ochre: The Curious Afterlife of the Red Lady of Paviland*. New York: Harvard University Press.

Sparacello, V.S. and Pearson, O.M. (2010). The importance of accounting for the area of the medullary cavity in cross-sectional geometry: A test based on the femoral midshaft. *American Journal of Physical Anthropology*, 143(4), pp.612–624.

Spina, A.A. (2007). The plantaris muscle: anatomy, injury, imaging, and treatment. *The Journal of the Canadian Chiropractic Association*, 51(3), pp.158–165.

Sterling, D.A., O'Connor, J.A. and Bonadies, J. (2001). Geriatric falls: injury severity is high and disproportionate to mechanism. *The Journal of Trauma*, 50(1), pp.116–119.

Stevens, R. (2006). Gray's Anatomy for Students. *Annals of the Royal College of Surgeons of England*, 88, pp.513–514.

Stini, W.A. (1990). "Osteoporosis": Etiologies, prevention, and treatment. *American Journal of Physical Anthropology*, 33(S11), pp.151–194.

Stock, J.T. (2006). Hunter-gatherer postcranial robusticity relative to patterns of mobility, climatic adaptation, and selection for tissue economy. *American Journal of Physical Anthropology*, 131(2), pp.194–204.

Stock, J.T., O'Neill, M.C., Ruff, C.B., Zabecki, M., Shackelford, L. and Rose, J.C. (2011). Body Size, Skeletal Biomechanics, Mobility and Habitual Activity from the Late Palaeolithic to the Mid-Dynastic Nile Valley. In R. Pinhasi & J. T. Stock, eds. *Human Bioarchaeology of the Transition to Agriculture*. Chichester, UK: John Wiley & Sons, Ltd, pp. 347–367.

Stock, J.T. and Pfeiffer, S.K. (2004). Long bone robusticity and subsistence behaviour among Later Stone Age foragers of the forest and fynbos biomes of South Africa. *Journal of archaeological science*, 31(7), pp.999–1013.

Stock, J.T. and Pinhasi, R. (2011). Introduction: Changing Paradigms in Our Understanding of the Transition to Agriculture: Human Bioarchaeology, Behaviour and Adaptaion. In R. Pinhasi & J. T. Stock, eds. *Human Bioarchaeology of the Transition to Agriculture*. Chichester: John Wiley & Sons, pp. 1–14.

Stock, J.T. and Shaw, C.N. (2007). Which Measures of Diaphyseal Robusticity Are Robust? A Comparison of External Methods of Quantifying the Strength of Long Bone Diaphyses to Cross-Sectional Geometric Properties. *American Journal of Physical Anthropology*, 134(July), pp.412–423.

Stringer, C.B., Trinkaus, E., Roberts, M.B., Parfitt, S.A. and MacPhail, R.I. (1998). The Middle Pleistocene human tibia from Boxgrove. *Journal of Human Evolution*, 34(5), pp.509–547.

Swaddling, J. (1980). *The Ancient Olympic Games*. 2nd ed. Austin, TX: University of

Texas.

Sweeney, D. (2011). Sex and Gender. *UCLA Encyclopedia of Egyptology*. Los Angeles: UCLA Press.

Takebe, K., Nakagawa, A., Minami, H., Kanazawa, H. and Hirohata, K. (1984). Role of the fibula in weight-bearing. *Clinical Orthopaedics and related research*, 184, pp.289–292.

Thambyah, A. (2008). How critical are the tibiofemoral joint reaction forces during frequent squatting in Asian populations? *The Knee*, 15(4), pp.286–294.

Thambyah, A. and Pereira, B.P. (2006). Mechanical contribution of the fibula to torsion stiffness in the lower extremity. *Clinical Anatomy*, 19(7), pp.615–620.

Thomas, R. (2008). The origin and use of ceramics on the islands of Mis and Umm Muri, in the Late Meroitic to Christian. *Sudan & Nubia*, 12, pp.64–72.

Thompson, A.H., Chaix, L. and Richards, M.P. (2008). Stable isotopes and diet at Ancient Kerma, Upper Nubia (Sudan). *Journal of Archaeological Science*, 35(2), pp.376–387.

Thompson, D.W. (1948). *On growth and form*. 2nd ed. Cambridge: Cambridge University Press.

Toohey, K. and Veal, A.J. (2007). *The Olympic Games: A social science perspective*. Wallingford, UK: CABI.

Tothill, J.D. (1948). *Agriculture in the Sudan: Being a handbook of agriculture as practiced in the Angle-Egyptian Sudan*. London: Oxford University Press.

Toulmin, C. (1992). *Cattle, Women, and Wells: Managing Household Survival in the Sahel*. Oxford: Clarendon Press.

Trigger, B.G. (1983). *Ancient Egypt: A social history*. Cambridge: Cambridge University Press.

Trilha Juniour, M., Fancello, E.A., De Mello Roesler, C.R. and More, A.D.O. (2009). Three-Dimensional Numerical Simulation of Human Knee Joint Mechanics. *Acta Ortopedica Brasilia*, 17(2), pp.18–23.

Trinkaus, E. (1975). Squatting among the neandertals: A problem in the behavioral interpretation of skeletal morphology. *Journal of archaeological science*, 2(4), pp.327–351.

Trinkaus, E. (2009). The Human Tibia from Broken Hill, Kabwe, Zambia. *PaleoAnthropology*, pp.145–165.

Trinkaus, E. and Ruff, C.B. (2012). Femoral and tibial diaphyseal cross-sectional geometry in Pleistocene Homo. *Paleoanthropology*, pp.13–62.

Trinkaus, E., Stringer, C.B., Ruff, C.B., Hennessy, R.J., Roberts, M.B. and Parfitt, S.A. (1999). Diaphyseal cross-sectional geometry of the Boxgrove 1 Middle Pleistocene human tibia. *Journal of Human Evolution*, 37(1), pp.1–25.

Trotter, M. and Gleser, G.C. (1952). Estimation of stature from long bones of American Whites and Negroes. *American Journal of Physical Anthropology*, 10(4), pp.463–514.

Trouilloud, P., Dia, A., Grammont, P., Gelle, M.C. and Autissier, J.M. (1988). Variations in the calcaneo-fibular ligament (lig. calcaneofibulare). Application to the kinematics of the ankle. *Bulletin de l'Association des Anatomistes*, 72(216), pp.31–35.

Turner, M.D. (2004). Political ecology and the moral dimensions of "resource conflicts":

the case of farmer–herder conflicts in the Sahel. *Political geography*, 23(7), pp.863–889.

Turner, W. (1895). On human remains found in caves at Oban, Argyllshire. *Proceedings of the Society of Antiquaries of Scotland*, 29, pp.410–438.

Vallois, H.-V. (1912). Considerations sur la forme de la section transversale du tibia chez les Lemuriens, les Singes et l'Homme. *Bulletins et memoires de la Societe d'anthropologie de Paris*, 6(3), pp.248–291.

Vallois, H.-V. (1938). Les méthodes de mensuration de la platycnémie ; étude critique. *Bulletins et Mémoires de la Société d'anthropologie de Paris*, 9(4), pp.97–108.

Van Caenegem, E., Wierckx, K., Taes, Y., Dedecker, D., Van de Peer, F., Toye, K., Kaufman, J.M. and T'Sjoen, G. (2012). Bone mass, bone geometry, and body composition in female-to-male transsexual persons after long-term cross-sex hormonal therapy. *The Journal of Clinical Endocrinology and Metabolism*, 97(7), pp.2503–2511.

Ved, N. and Haller, J.O. (2002). Periosteal reaction with normal-appearing underlying bone: a child abuse mimicker. *Emergency Radiology*, 9(5), pp.278–282.

Vickerton, P., Jarvis, J.C., Gallagher, J.A., Akhtar, R., Sutherland, H. and Jeffery, N. (2014). Morphological and histological adaptation of muscle and bone to loading induced by repetitive activation of muscle. *Proceedings. Biological Sciences / the Royal Society*, 281(1788), p.20140786.

Villotte, S., Castex, D., Couallier, V., Dutour, O., Knüsel, C.J. and Henry-Gambier, D. (2010). Enthesopathies as occupational stress markers: evidence from the upper limb. *American Journal of Physical Anthropology*, 142(2), pp.224–234.

Villotte, S. and Knüsel, C.J. (2013). Understanding Entheseal Changes: Definition and Life Course Changes. *International Journal of Osteoarchaeology*, 23(2), pp.135–146.

Wadley, L. (1997). Where have all the dead men gone? Stone Age burial practices in South Africa. In L. Wadley, ed. *Our gendered past: Archaeological studies of gender in Southern Africa*. Johannesburg: Witwatersrand University Press, pp. 107–134.

Waldron, T. (2009). *Palaeopathology*. Cambridge: Cambridge University Press.

Wallace, I.J., Gupta, S., Sankaran, J., Demes, B. and Judex, S. (2015). Bone shaft bending strength index is unaffected by exercise and unloading in mice. *Journal of Anatomy*, 226(3), pp.224–228.

Wanner, I.S., Sosa, T.S., Alt, K.W. and Tiesler Blos, V. (2007). Lifestyle, Occupation, and Whole Bone Morphology of the Pre-Hispanic Maya Coastal Population from Xcambo Yucatan, Mexico. *International Journal of Osteoarchaeology*, 268(May 2005), pp.253–268.

Warren, M.P. (1999). Health issues for women athletes: exercise-induced amenorrhea. *The Journal of Clinical Endocrinology and Metabolism*, 84(6), pp.1892–1896.

Weedman, K. (2006). Gender and Ethnoarchaeology. In Sarah Milledge Nelson, ed. *Handbook of Gender in Archaeology*. Oxford: AltaMira, pp. 247–294.

Weiss, E., Corona, L. and Schultz, B. (2012). Sex differences in musculoskeletal stress markers: Problems with activity pattern reconstructions. *International Journal of Osteoarchaeology*, 22(1), pp.70–80.

Wells, J.C.K. (2012). Sexual dimorphism in body composition across human populations:

associations with climate and proxies for short- and long-term energy supply. *American Journal of Human Biology*, 24(4), pp.411–419.

Welsby, D.A. (2003). *Survey Above the Fourth Nile Cataract*. Oxford: BAR International Series.

Welsby Sjostrom, I. (2001). The pottery from the survey. In D. A. Welsby, ed. *Life on the Desert Edge*. London: Sudan Archaeological Research Society, pp. 230–248.

Wendorf, F. and Said, R. (1967). Paleolithic Remains in Upper Egypt. *Nature*, 215, pp.255–47.

Wengrow, D. (2010). *What Makes Civilization? The Ancient Near East and the Future of the West*. Oxford: Oxford University Press.

Wescott, D.J. (2006). Effect of Mobility on Femur Midshaft External Shape and Robusticity. *American Journal of Physical Anthropology*, 213, pp.201–213.

Wescott, D.J., Cunningham, D.L. and Hunt, D.R. (2014). Temporal trends in femoral diaphyseal torsional asymmetry among the Arikara associated with postural behavior. *American Journal of Physical Anthropology*, 154(4), pp.512–524.

Weston, D.A. (2011). Nonspecific Infection in Paleopathology: Interpreting Periosteal Reactions. In A. L. Grauer, ed. *A Companion to Paleopathology*. Oxford, UK: Wiley-Blackwell, pp. 492–512.

White, C., Longstaffe, F.J. and Law, K.R. (2004). Exploring the effects of environment, physiology and diet on oxygen isotope ratios in ancient Nubian bones and teeth. *Journal of archaeological science*, 31(2), pp.233–250.

White, S. (2015). Virtual Archaeology - The NextEngine Desktop Laser Scanner. *Aquatic Invasions*, 18(0), p.41.

White, T.D., Black, M.T. and Folkens, P.A. (2012). Assessment of Age, Sex, Stature, Ancestry, and Identity of the Individual. In *Human Osteology*. Elsevier, pp. 379–427.

Wilczek, J., Monna, F., Barral, P., Burlet, L., Chateau, C. and Navarro, N. (2014). Morphometrics of Second Iron Age ceramics – strengths, weaknesses, and comparison with traditional typology. *Journal of archaeological science*, 50, pp.39–50.

Willcocks, W. and Brown, R.H. (1899). *Egyptian Irrigation*. Spon & Chamberlain.

Williams, A. and Logan, M. (2004). Understanding tibio-femoral motion. *The Knee*, 11(2), pp.81–88.

Wilson, L.A.B. and Humphrey, L.T. (2015). A virtual geometric morphometric approach to the quantification of long bone bilateral asymmetry and cross-sectional shape. *American Journal of Physical Anthropology*, 158(4), pp.541–556.

Wolff, J. (1892). *The Law of Bone Remodeling*. Berlin.

Woodburn, J. (1968). An Introduction to Hadza Ecology. In *Man the Hunter*. Hawthorne, NY: Aldine, pp. 49–55.

Yiannakopoulos, C.K., Kanellopoulos, A.D., Trovas, G.P., Dontas, I.A. and Lyritis, G.P. (2008). The biomechanical capacity of the periosteum in intact long bones. *Archives of orthopaedic and trauma surgery*, 128(1), pp.117–120.

Yilmaz, D., Ersoy, B., Bilgin, E., Gümüşer, G., Onur, E. and Pinar, E.D. (2005). Bone mineral density in girls and boys at different pubertal stages: relation with gonadal steroids, bone formation markers, and growth parameters. *Journal of Bone and Mineral Metabolism*, 23(6), pp.476–482.

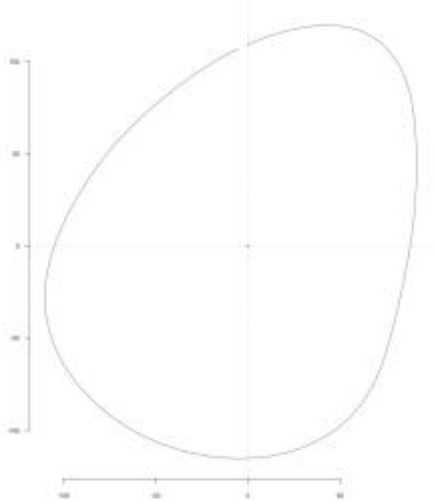
Zhou, J., Yu, W. and Ng, S.P. (2012). Studies of three-dimensional trajectories of breast movement for better bra design. *Textile Research Journal*, 82(3), pp.242–254.

Zipfel, B., DeSilva, J.M., Kidd, R.S., Carlson, K.J., Churchill, S.E. and Berger, L.R. (2011). The foot and ankle of Australopithecus sediba. *Science (New York)*, 333(6048), pp.1417–1420.

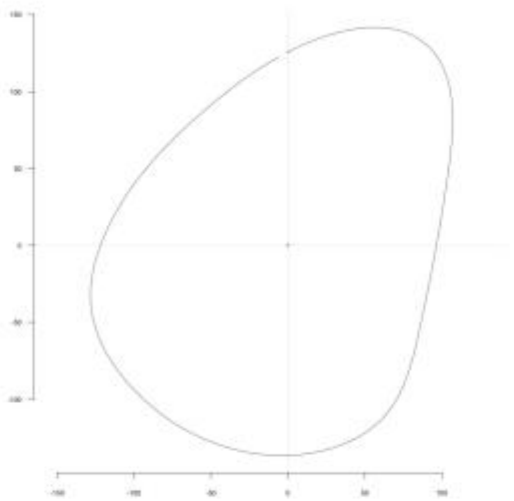
Zurawski, B. (2005). Fourth Cataract Survey and Excavation in Shemkhiya, Dar el-Arab and Saffi Island. In B. Zurawski, ed. *Polish Archaeology in the Mediterranean*. Warsaw: University of Warsaw, pp. 323–335.

Zurawski, B. (2002). Survey and Excavations between Old Dongola and ez-Zuma. *Sudan & Nubia*, 6, pp.71–85.

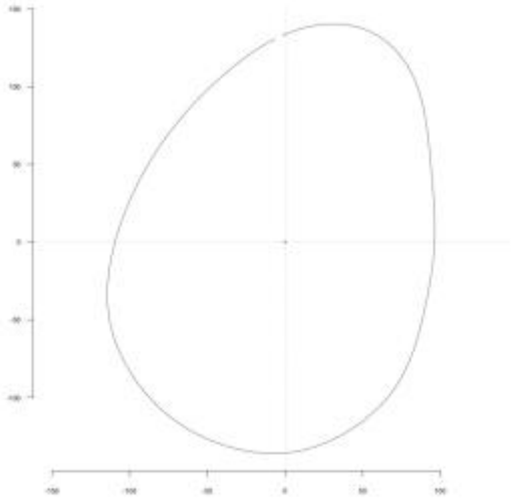
Appendix: Mean tibial midshaft cross-section shapes



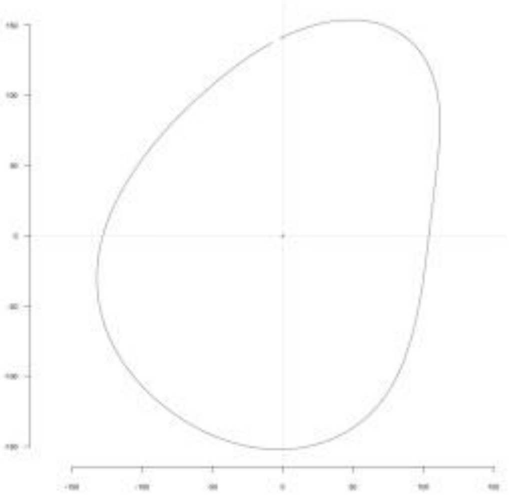
Females



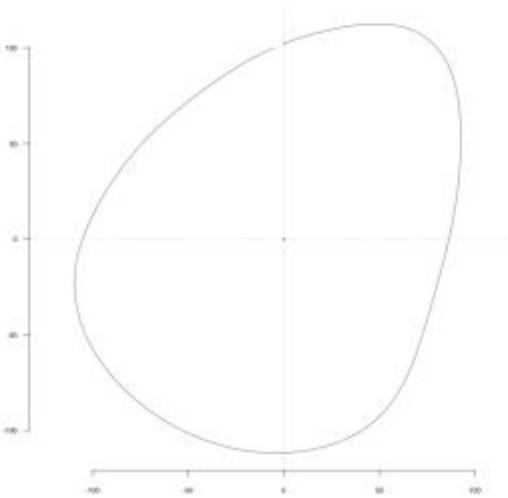
Males



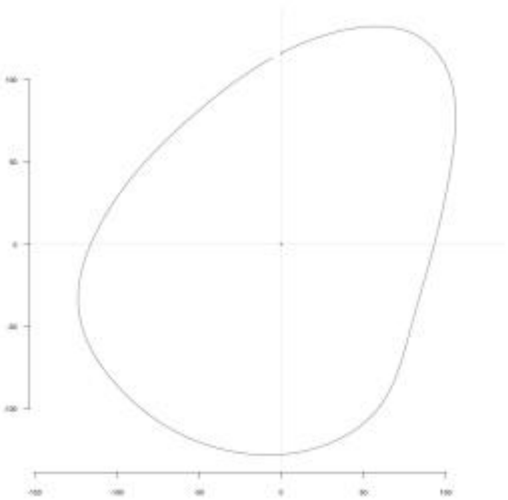
Jebel Moya females



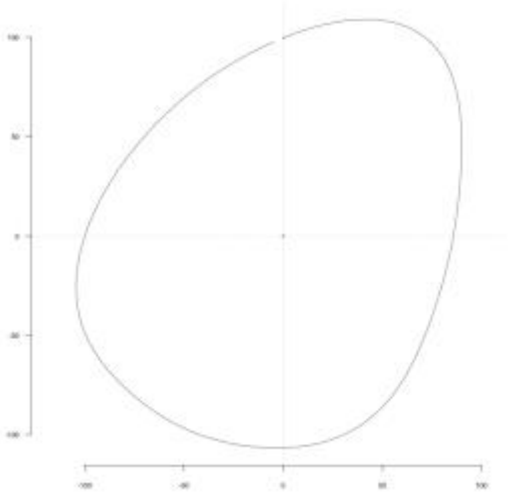
Jebel Moya males



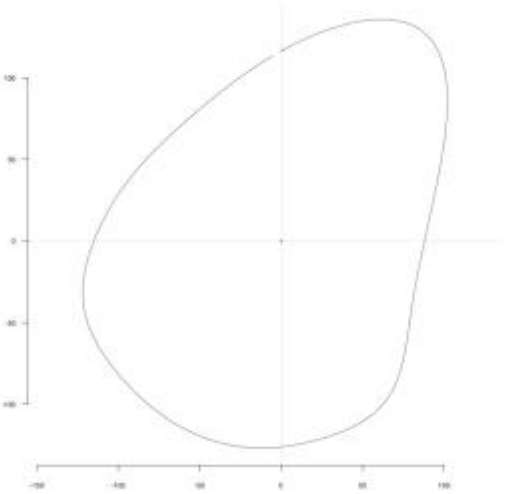
3-J-18 females



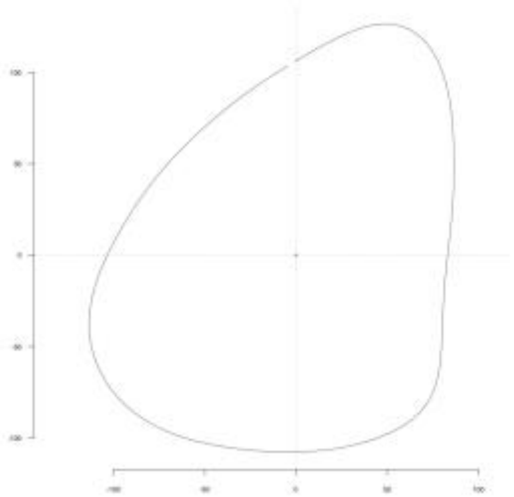
3-J-18 males



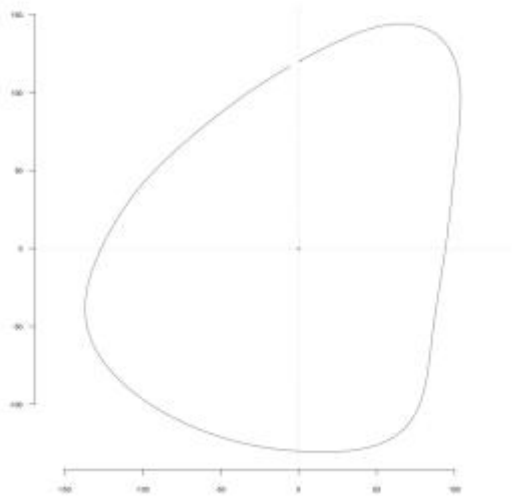
Gabati females



Gabati males



Chichester females



Chichester males