SEXUAL DIMORPHISM AND THE SHAPE OF THE PROXIMAL TIBIA IN A RADIOGRAPHIC SAMPLE

by

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ABSTRACT

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Under the Supervision of Dr. Fred Anapol and Dr. Joseph P Gray

This study investigates the use of radiographs to determine sexual dimorphism in the shape of the tibia. The goal of the research was to identify a small set of markers that would allow researchers to efficiently and accurately determine a person's sex from a radiograph of the proximal tibia.

The sample consisted of radiographs including 75 females and 46 males ranging in age from 21 to 81. Measurements were taken on 27 points around the area of the knee including the tibia, patella, and femur. The measurements were converted into a compositional data set and the log-ratios between all measurements were analyzed with a classification and regression tree procedure (CART) to predict sex. The sample was divided into training and testing sets prior to analysis. In the training data only three log-ratios were needed to achieve an accuracy of 87.78% for sex determination. The accuracy rate fell to 70.00% in the testing data. This success rate compares favorably with the results achieved by Toon (2014) in her osteological analysis of 200 tibia from the WM Bass Donated Skeletal Collection. Toon used a geometric morphometric approach to define a linear discriminant function that achieved a cross-validated accuracy rate of 57% – 59%. The approach illustrated in my study has the advantage of achieving a higher accuracy while requiring many fewer data points.

Two extensions of the present study are required before its usefulness to forensic anthropologists and archaeologists can be evaluated. First, it must be established whether the log-ratios that identified as useful in predicting sex by the CART procedure are consistent across populations. Second, the log-ratios need to be validated as useful when used to analyze actual, physical skeletal remains.

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Chapter one: Introduction and Literature Review

Introduction

The non-reproductive structural differences between males and females within a species is known as sexual dimorphism, which includes the consideration of body size, and body shape (Moore 2012:93). This biological difference is useful when identifying skeletal remains. Sex determination is an important part of a biological profile because it provides further correlating factors between the skeleton and a potential identity. Determining the sex of an individual immediately reduces the links to possible biological profiles by fifty percent.

It is more difficult to determine the sex of a subadult than an adult because skeletons do not exhibit great variation between sexes before puberty. As individuals grow and develop, their skeletons become more distinct to their sex. This is a result of puberty, genetics, and individual biomechanics. Males and females express morphological traits differently and by analyzing intrinsic (internal) and extrinsic (external) influences of sexual dimorphism, one can better understand existing morphological differences. Extrinsic factors, such as experiences, activities, habits, and trauma mark bone and create wear. In response to these factors, the human body recognizes the biomechanical stress on the bones and creates more bone; finding places that are the most stressed and making them stronger to maintain or surpass the stress produced by that activity. The amount of force and stress applied to bones due to locomotion can affect the expression of sexual dimorphism differently in males and females. Those who are more active and move around a lot may exhibit more robust skeletons than those who are more sedentary (Toon 2014:4). The amount and type of activity an individual does during life can affect the robusticity of the remains after death.

Robusticity is the size of a bone relative to the mechanical loads placed on it. The variation in robusticity is a result of adaptions to mechanical loads (Imber 2003:2). Robusticity is acknowledged to be a representation of bone's strength relative to size and is identified based on thickness divided by length. (Lewis 1999:1) The robusticity is greater in bones that carry more mechanical loads or bear more stress/strain and can be compared to landmarks that have less loads placed upon them, such as the cranial features/landmarks. The purpose of this study is to identify if sexual dimorphism influences the shape or size of the tibia and if it can be utilized in providing enough information towards a sex identity to add to a biological profile.

The interaction between bone and muscle is visible in areas associated with attachment sites in relation to the biomechanical stressors consistent with activities. Below is an example of where muscles and tendons are articulated with the bones in the knee. The use and size of these muscles affect the size of the bones beneath.

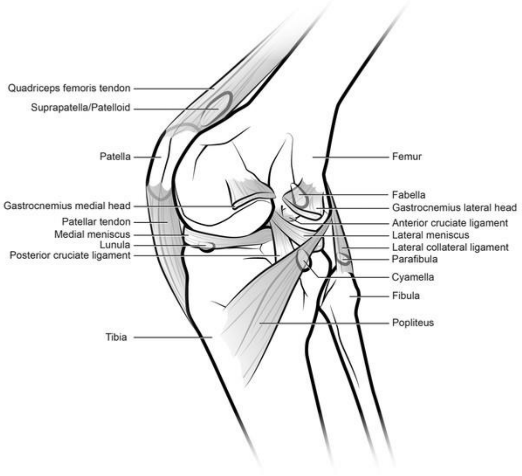


Figure 1 Image of muscle and ligament insertions into the knee adapted from Samuels 2017: "Generalized knee showing sesamoid bones found in various mammals, although possibly no species includes all of these (patella, lunula, cyamella, fabella and parafibula). Also shown are relevant muscles, ligaments, and other anatomical elements that lie close to the sesamoids of the knee joint. The knee is in the medial view and the medial collateral ligament has been removed. Illustration by Manuela Bertoni" (Samuels, 2017. 13).

Bone responds to the external forces acting upon it by altering its shape, structure, and mass. Muscle growth creates osteoblastic activity, which is most present in muscle, tendon, and ligament insertion points. These points are near the proximal and distal ends of bone and are often identifiable as tubercles or tuberosities, rough surfaces, or elevated/depressed/remodeled surfaces when locating landmarks on bone (Mariotti 2004: 146). The growth and change of these landmarks or musculoskeletal markers can suggest load-induced remodeling.

The ability to recognize these landmarks on bone assists anthropologists in determining the biological profile of skeletal remains. Landmarks can lead to information about population trends and occupational stressors. The interactions bone has with the muscular and connective tissues is dynamic and influenced by more than just one event. The etiology of most musculoskeletal changes is influenced by age, sex, pathology, physical activity, and individual variation.

Anthropologists are skilled in the identification sexual dimorphism within skeletal remains; however, there are issues with current anthropological study in retrieving and preserving remains. Using the shape of the tibia and digital technology to enhance skeletal analysis may be a solution to addressing some issues in the field. Radiographs are inexpensive, more accessible, and have the ability to document live populations.

This study investigates the difference in shape and size located in knee radiographs of living people. The focus was not only to determine whether sexual dimorphism contributes to the shape of the proximal tibia, but if excess measurements could be eliminated in order to expediate sex estimation. The two guiding hypotheses were:

1. The shape and the size of the knee will be sexually dimorphic
2. One can use the size and shape of a knee as a contribution to the identification of the sex of an individual from a radiograph.

This study showcased the potential to utilize radiographs to analyze possible patterns within populations. The main analysis within the knee was the size of the tibial tuberosity and length of the patella, recognizing the difference between the variables of size and shape.

Literature Review

Sexual dimorphism in skeletal remains

Sexual dimorphism is present throughout the vertebrates. It is defined as the differences in size, shape, and structure found between males and females of the same species (Frayer, Wolpoff 1985:429). Sexual dimorphism in humans is commonly reported as a larger stature, more robust cranial and facial features, and a greater muscularity in males over females. Frayer writes, “In all human groups, male tooth size exceeds that for females, females store more subcutaneous fat, males have proportionally more muscle fiber, pre and postnatal hormonal levels differ, growth rates vary, and diseases affect the sexes differently” (Frayer, Wolpoff 1985:470).

While these variants differ between the sexes, individually, they cannot contribute to a full identification of sex and only occur in adults. As such, many are regarded as the result of hormonal events that occurred at puberty. Males typically reach puberty three to five years after females resulting in a larger stature and differences in plasticity. Frayer writes, “Differences in the plasticity of males and females, along with the underlying genetic differences, provide evidence for a long-term selection regime in which human males and females, each in their own ways, have responded to reproductive, environmental, and cultural factors” (Frayer, Wolpoff 1985:429).

In order to understand how sex relates to robusticity in skeletal remains, it is important to acknowledge the variance between sexes and muscle development. Most differences are a result of hormone influences. In males, the changes in bone and muscle during puberty are dominated by the increasing levels of testosterone and IGF-1, which result in increased muscle mass and strength. Lang explains that, in men, "muscle and bone is more parallel in nature and the peak values of cortical area and muscle cross-sectional area tend to coincide within half a year in men" (Lang, 2011: 2). This differs from females who produce less testosterone and more estrogen. Their bone mass, but not total cross sectional area, increases more rapidly than the surrounding muscles. Lang further explains "The increase in bone mass appears to take the form of increased endosteal apposition, rather than periosteal apposition" (Lang, 2011: 3).

Lang writes, "Large decreases in estrogen levels in women appears to diminish the skeleton's responsiveness to exercise more than in men. In contrast, the aging of the muscle-bone axis in men is a function of age related declines in both hormones" (Lang, 2011: 3). The increase in testosterone creates more potential for males to develop muscle. The shift in estrogen that occurs in pregnancy and menopause can cause osteopenia and osteoporosis. This occurs due to the increase of osteoclasts and increases the risk for fracture. Lang writes, "Skeletal fractures occur when bones are subjected to mechanical loads, which exceed their strength. Diminished skeletal strength is a primary risk factor for fracture, and gender differences in skeletal structure and strength play a powerful role in determining gender differences in fracture risk" (Lang, 2011: 1). The stronger the muscle, the stronger the bone.

The structure of the skeleton adapts to long term loads put on the skeleton. This occurs as a result of physical activity as the most powerful loading forces are bestowed by muscles, which, as Lang writes, "must exert enough force to move bones while acting against extremely short lever arms" (Lang, 2011: 1). The largest sex difference that occurs in bone is the bone-muscle relationship and the resulting bone strength. Hormones influence interactions with muscle tissues, which alter the mass and strength. This affects the stress placed on the bone. The mechanical aspect of the muscle to bone relationship is gender specific. Males have been found to display higher total and cortical bone cross sectional areas in the hip, tibia, and radius. However, the volumetric density values were similar between the sexes. Lang writes, "Women have higher values of bone in relation to muscle, but a lower percentage of the variation in cortical area in women is explained by muscle mass" (Lang, 2011:2).

The biggest indicator of sex in the bone-muscle relationship is the decrease in estrogen that causes bone resorption. Low levels of estrogen affect the skeleton by decreasing mechanical sensitivity. Lang writes, "Thus, as with androgens, estrogens affect the muscle bone system by decreasing the effect of muscle contractions on bone, leading potentially to decreased efficacy of resistance exercise in men as well as women with increasing age" (Lang, 2011:4).

Research has uncovered that males have greater bone mineral content (BMC) and bone mineral density (BMD) than females at the hip and in the tibia. This difference was related to the degree of cortical thickness in the tibia. Cortical thickness is affected by muscle mass rather than general robusticity. The differences in bone mass "confer greater skeletal integrity" in males reducing the risk of stress and osteoporotic fractures. (Nieves 2011:1)

The measurement of cortical bone can help determine bone strength. The amount of cortical bone can lead to understandings of the etiology of osteoporotic fractures, which can lead to further treatments. In the past, researchers have used CT scans to measure cortical thickness, density, and mass. These measurements have varied based on sex, ethnicity, and pathology.

There are many differences found between the sexes regarding skeletal change and cortical remodeling. Ruff (2006) explains that these differences occur as a result of variations related to stress or strain levels. In the femur and tibia, these result from mechanical loadings of the lower limb. This may infer that the robusticity found in the tibia may be sexually dimorphic due to varied mechanical loading. Bone forms a denser amount of cortical bone in response to higher stress. The larger the stress, the larger the muscle capacity, which, consequently, creates denser cortical bone. Males consistently appear with a larger muscle capacity. Muscle capacity is a measurement of the muscle strength (the maximum force that can be exerted in one muscle contraction), muscle power (the product of muscle force and contraction velocity), and muscle function (Ruff, 2006:iii). The muscle capacity is influenced by the degree of testosterone available to produce the muscle. Males appear to have denser cortical bone as a response to having a larger muscle capacity arguing that their muscle capacity is sexually dimorphic.

Sexual dimorphism in the tibia

Sex can be determined through many bones in the human skeleton. The most accurate ways to determine sex is through observing the pelvis or the skull but when they are not present or are fragmented beyond recognition, other bones can also be useful in sex determination. The tibia is useful because it resists erosive forces and keeps its basic anatomical shape long after death (Kirici 1999:i). Researchers have studied sexual dimorphism in the tibia from varying populations. Different techniques of analysis were utilized by different authors.

The tibia varies in size due to stature and robusticity. Iscan utilized morphometric analysis to discover if the tibia is variable by sex as well. They measured the tibial length, circumference, and the anteroposterior and transverse measurements at the nutrient foramen. "It was found that the circumference alone could give, on the average, 80% accuracy in determining sex" (Iscan 1984:2). They then explained that the additional measurements included in their discriminant function analysis increased the accuracy by about 4%. This research argues that muscular hypertrophy may be responsible for the sexual dimorphism stating: "Comparisons of this study with those on the femur indicated that sexual dimorphism in the tibia was a result not only of the general growth and musculo-skeletal activity, but also of the genetic structure of the population, i.e., racial variation" (Iscan 1984:2).

Kirici utilized discrimination studies directed to the proximal part of the tibia in Turkish cadavers. Kirici writes, "The results indicated that classification accuracy ranged from 89% in the right and 87% in the left for biarticular breadth. There was a minimal difference between the sides and the height of the medial malleolus" (Kirici, 1999:i). This sample exhibited sexual dimorphism in the distal and proximal dimensions of the tibia.

Although there are set formulae used to determine the sex of skeletal remains, the results are not always consistent throughout populations. Nanayakkara developed seven standard variables on the tibia that can determine sex in a Sri Lankan population. These variables include: "the maximum length of tibia, proximal epiphyseal breadth, distal epiphyseal breadth, minimum circumference of shaft, anteroposterior diameter at nutrient foramen, transverse diameter at the nutrient foramen (TDNF), and circumference at the nutrient foramen" (Nanayakkara, 2019: 2). The tibiae were analyzed to determine sexual dimorphism, which was confirmed. Nanayakkara writes, "The most dimorphic single parameter in males was the TDNF providing an accuracy of 92.9%, while in females, the minimum circumference of shaft provided an accuracy of 70.4%.

The best multivariate equation utilizing two tibial dimensions resulted in an accuracy of 80.2% after cross-validation" (Nanayakkara, 2009: 6).

Martens tested a series of non-pathological tibias and femurs for torsional loading at high strain rates (Martens 1981:113). These signs of loading at high strain rates would visibly alter the robusticity of the bones. Martens suggested using geometrical parameters to predict mechanical behavior of a bone structure. This was done by testing the high variation of elasticity of bone structures and its effect on torsional loading. The elasticity of the bone is influenced by the amount of collagen present in the bone. The amount of collagen is influenced by hormones. For example, post-menopausal women lose collagen in their skin and bones, which causes wrinkles and osteoporosis.

In another study, the geometrical properties of the human tibia were reviewed to identify possible landmarks that should be measured in radiographs. The geometric properties of four left human tibiae were measured. The measurements included: the antero-posterior and medio-lateral planes, and load-bearing area of cortical bone and the orientation of the principal axes have been determined at seven levels along the length of the tibia. (Minns 1975:253) These landmarks were measured to determine load and strain placed on the tibia.

The aim of Santos' study was to differentiate males and females based on morphometric aspects of tibiae. Santos writes,

> "The tibia is a long bone that supports a large part of the body weight and is directly related to movements of the lower limbs. This bone also has strong dimorphic characteristics. The proximal portion of the tibia expands, forming a surface to support the body weight, the force of which is transmitted through the femur. The medial and

> lateral condyles, intercondylar area and tibial tuberosity are located at this end of the tibia" (Santos 2010:3).

Ten measurements were made on the joint face of the tibial plateau. These measurements were reviewed to aid in the determination of the measurements that will be analyzed in the radiographs of the present study. The ten measurements included: "Anteroposterior diameter of the joint surface of the medial condyle (APM), Transverse diameter of the joint surface of the medial condyle (TM), Anteroposterior diameter of the joint surface of the lateral condyle (APL), Transverse diameter of the joint surface of the lateral condyle (TL), Anterior transverse measure of inter-condyle area (ATI), Posterior transverse measure of inter-condyle area (PTI), Middle transverse measure of inter-condyle area (MTI), Anteroposterior measure of inter-condyle area (API), Anterior measure of intercondyle area (AI), and Posterior measure of inter-condyle area (PI)" (Santos 2018:1).

The analysis of these measurements demonstrated sexual dimorphism. This research explained that the largest difference between sexes was found for the anterior transverse measurement of the intercondylar area and the anteroposterior measurement of the intercondylar area. This analysis determined that the tibia bone could be used for sex estimation of an unidentified individual. There was presence of sexual dimorphism in the tibia meaning the tibia could possibly be utilized in sex identification.

Reviewing the research above allows for the reasoning that the tibia is an important bone in distinguishing sexual dimorphism within a sample. Not only are there displayed biomechanical factors that influence robusticity, but the amount and type of hormones influence the shape of the tibia. This may allow for future utilization of the different effects of sexual dimorphism within the tibia to aid in the possible identification of an individual's sex.

Past Research and Methods in Tibial Shape Analysis

There are two sets of research that guided my focus on the use of shape when identifying sexual dimorphism within the tibia. Both Toon and Brzobohata used geometric morphometrics and cross-validation to analyze their sample. Geometric morphometrics is an analysis that allows the researcher to place the morphological shape of bones into a statistical framework to answer questions on a variety of topics, including sexual dimorphism. Cross-validation (C-V) "generates success rates of discriminant function by leaving one individual out of the discriminant function analysis, generating a function from the remaining individuals in the sample, and then applying the function to the induvial that was left out of the analysis" (Toon 2014: 37). While both projects resulted in similar conclusions, their samples were very different considering age, race, and the use of 3D representations of the remains.

Toon studied the proximal tibia in modern Caucasian American population of 100 male and 100 female tibiae. Toon's research cites Spradley and Jantz who studied the accuracies of different postcranial bones in sex estimation. Toon explains Spradley and Jantz found that measurements from the tibia resulted in a higher accuracy rate than using measurements from the cranium in a modern Caucasian American population. This conclusion was not consistent in African American populations and demonstrated that sexual dimorphism varies from population to population. Variation is largely due to size differences between males and females. This variation created problems when identifying sexual dimorphism using traditional morphometrics because these methods rely on linear measurements and cannot establish conclusions about shape differences. To ensure an accurate depiction of her measurements, Toon used geometric morphometrics to analyze the tibia. She chose the tibia because it is "one of the weight-bearing bones of the body and subjected to regular stress at the proximal joint, and because males and females have been noted to be subject to different amounts of locomotion stressors, the tibia has been noted to exhibit sexual dimorphism" (Holland 1991; Frelat et al. 2012: 227).

Toon also states that from Spradley and Jantz, they found that the epiphyseal breadth of the proximal tibia yielded the highest accuracy of 90%. Toon writes,

> "This indicates that simply by taking a single measurement from the proximal tibia, sex can be accurately estimated with a 90% success rate. Their cross-validated classification rates for the tibia resulted in a 91.65% accuracy rate. From this, the proximal tibia clearly has some merit as a sexually dimorphic area of the skeleton"(Toon 2014: 17) .

It has also been found that the tibial length and circumference at the nutrient foramen level is significantly sexually dimorphic. However, due to the likelihood of fragmented remains, the total length of any long bones many be difficult to collect.

In a white South African population, Steyn and Iscan found that tibial epiphyses were significantly sexually dimorphic. Toon summarizes that

> "the proximal epiphyseal breadth of the tibia yielded a 86.8% accuracy rate alone, while the highest accuracy rate of 90.6% was achieved using a combination of the proximal and distal epiphyseal breadth of the tibia, and a combination of proximal epiphyseal breadth, anterior-posterior diameter, transverse breadth, minimum circumference, and distal epiphyseal breadth of the tibia" (Toon 2014: 19).

All of Toon's research suggested that the tibia would present in a positive analysis of sexual dimorphism within the tibia but due to the variation form different populations, Toon explained that she needed to exclude size from the equation. Toon writes, "The purposes of the present study was to determine whether the shape of the proximal tibia contributes to sexual dimorphism and whether it can be useful in assigning sex to unknown individuals using geometric morphometrics.” (Toon 2014: 22)

Through the use of geometric morphometrics, Toon was able to analyze shapes of her sample. To do so, she had to turn the tibia into a configuration of landmarks selected due to relevance to the bone. For instance, she selected the tibial plateau and the intercondylar eminence because these are landmarks that will be found on each tibia regardless of the size or population. Toon used a generalized Procrustes analysis to superimpose each set of landmarks to correct for orientation, size, and location differences between each tibia. This was important because she digitalized her entire sample for analysis.

Toon also used a principal components analysis to examine the overall variations between sexes and discriminant function analysis to determine the accuracy in the differentiation of the shape between tibias. Toon writes, “Statistical analysis identifies the function that best separates the groups that are represented in the data. It focuses on the landmarks that exhibit maximum variation between groups” (Toon 2014: 37). The focus on the maximum variation between the groups inflated accuracy rates. To avoid this, Toon cross-validated the discriminant function.

The discriminant function analysis (DFA) confirms sexual dimorphism at the proximal tibia and the cross-validated DFA revealed accuracy rates of 58% between females and males. Toon writes, “Overall, the discriminant function was more successful at classifying females than males. These results indicate that the shape of the proximal tibia does exhibit sexual dimorphism, though the discriminant function developed from this sample may not be particularly useful for estimating sex” (Toon 2014: 49).

Toon revealed that the lateral side of the proximal tibia exhibits the greatest amount of shape variation, which is consistent with previous research. Toon's DFA achieved 73-77% accuracy and 57-59% accuracy in the cross-validated DFA. Toon states that size is still a more accurate measurement to determine sex, however, the variation between population makes the significance questionable.

On the other hand, Brzobohata, attempted to detect size and shape differences between the sexes of three samples from varying Czech population subsets throughout time. The first subset was from early medieval (9-10th century), the second subset was early 20th century, and the third, composed of 3D models from a modern 21st century sample. Brzobohata explains that the results from all three datasets showed pronounced sexual dimorphism. Brzobohata writes, "There were some sex-dimorphic characteristics common to all three samples, such as tuberosity protrusion, anteriorly bowed shaft and relatively larger articular ends in males. Diachronic comparisons also revealed substantial shape variation related to the most dimorphic area" (Brzobohata 2016:1).

Brzobohata explains that while tibial shape was important in determining sex, classification using tibial form was more successful than using tibial shape. The highest values of correct assignment (91.80% and 88.52%) were found using the form from the early 20th Czech population. This research suggests that the shape of the proximal tibia varies by sex. The shape changed throughout time but Brzobohata writes that the modern population exhibited the greatest variance in shape. Note the differences observed between male and female tibial shape (adapted from Brzobohata 2016:7)

Figure 2 Sexually Dimorphic Shape Variation

Male Female (adapted from Brzobohata 2016)

Although tibia shape aids in the determination of sexual dimorphism, it is not the only difference noted in tibiae between the sexes. The greater angle shown of the proximal, lateral aspect of the male tibia in the figure above may be due to the greater surface area in male condyles. There is a more curved shaft and an angled malleolus in males compared to females. Brzobohatá suggests that there is a definite division in robusticity due to sexual dimorphism. Brzobohatá used a surface-based methodology that enabled analysis of sexually dimorphic features throughout the shaft and articular ends of the tibia. (Brzobohata 2016:1)

Environmental conditions and hormonal factors can affect the shape of the tibia, but the most important influencer is physical load. Studies show that male growth is more sensitive to environmental agents, and an exploration into biomechanical research has shown that the biomechanical signature of mobility is more marked in the diaphysis of the tibia relative to the femur. The human tibia is an important skeletal element for identifying sex in both archaeological and forensic contexts due to its robustness and post-depositional resistance (Brzobohatá 2016:3).

Brzobohatá writes,

> “The degree of sexual dimorphism is considered to provide an indication of the general health status and environmental stress, with weaker manifestation in populations exposed to poorer living conditions, and vice versa: stronger SD is expressed in populations experiencing better living conditions and health status. Living conditions act through biological factors (nutrition and infections), both of which can affect adult body size.” (Brzobohatá 2016:3).

These characteristics were more exaggerated in the earlier populations due to an increase in activity and a cultural increase of sexually dimorphic occupations. Due to its consistent dimorphic traits, Brzobohatá regards the tibia as an important skeletal element for identifying sex.

The conclusions of Brzobohatá’s tests resulted in 76.79%-85.25% accuracy and state that excluding size had a major impact on the results (Brzobohatá 2016). The most notable conclusion was that the shape varied by sex throughout time. Brobohata wrties, “In general, female tibiae were more gracile and slender, with relatively smaller and narrower condyles and malleoli and a straighter shaft when viewed from the side. Female bone shafts progressively widened to the condyles and malleoli, which created a smooth transition between the shaft and the extremities” (Brzobohatá, 2016:11). (Fig 2)

These two researchers provided many examples of why the shape of the tibia was important for future sex estimation and biological profiles in archaeological and forensic cases. They both found that size of the tibia was more sexually dimorphic but was less dependable throughout samples, while shape could benefit from more research to find a more efficient manner of analysis.

Chapter two: Theoretical Framework

Although anthropology is divided into cultural and physical subfields, the two are inherently linked. The human skeleton is a physical example that represents the melding of culture, environment, biology, and genetics. It links past ancestry with current life action but is still constantly influenced by the world surrounding it. Social action and environmental influences impact an individual's life both cognitively and physically.

There are two theories within anthropology that explain this link: life course theory and embodiment theory. Agarwal defines life course theory as “a conceptual framework that approaches the examination of bone morphology in the past and united their interrogation of human life as a result of interrelated and cumulative events over not only the timeframe of individuals, but also over generations at the community level” (Agarwal, 2016:131) Life course theory connects an individual's historical, socioeconomic, and biological contexts with their skeletal remains. It represents a totality of life experiences, relaying responses to any exposures whether that be guided by social law or influence, by environmental incident, or biological adaptation. Life course theory helps inform the biological profile by correlating cultural influences with a biological response.

Life course theory reflects the impacts of social constructs and it provides a possibility to frame an individual's agency within a community. How the individual develops within a known social structure compared to the rest of the population may provide an inference to their autonomous actions. This would only influence the skeleton if it impacted development or created stressors that could affect them physically. For example, a soldier's decisions in combat, though socially guided, impact his or her physical being. Similar to the way one cannot identify religion or beliefs in material remains without symbolism, it is difficult to identify agency without a physical representation.

The key to life course approaches may be the concepts of trajectories and plasticity (Agarwal, 2016: 131)**.** An individual's development is malleable and can change direction or trajectory, along the phases of the life course. There are two approaches to life course theory: evolutionary developmental biology (EDB) and developmental systems theory (DST) (Robert et al., 2001; Hallgrimsson et al., 2002:954). EDB concepts revolve around embryology and fetal development. The greater influences in EDB that are noted here include genetics and the maternal environment. Although our genetics are influential in our development, DST elaborates on external variables that may have a greater influence on a life course.

DST includes inheritance but broadens to include ecological and social influences on development. Agarwal, Fausto-Sterling, and Beauchesne write, "While there is still uncertainty if or how non-genetic influences are inherited, particularly in relation to skeletal morphology, there is increasing evidence that non-genetic forces can significantly shape postnatal and skeletal morphology" (Fausto-Sterling, 2005; Agarwal and Beauchesne, 2011:132). One of the best examples of this in anthropological theory is Boas' anthropomorphic study of young European immigrants *(*Boas 1912:532). In this study he demonstrated that environmental changes, including changing cultural milieus, could produce changes in body size and shape in future generations. He used examples that showed the differences in growth, stature, and development that were triggered by the environment. This could include malnourishment, a lack of resources, a high stress environment like war time, or pathologies that impacted development. The stress in Boas' studies were focused on nutrition. Agarwal writes, "Since then, numerous migrant studies have confirmed the correlation of changing environments to changes in growth and development" (Agarwal 2016:133).

The degree of stunted growth in long bones is a good indicator of population stress. Agarwal writes, "Populations that show reduced stature show evidence of greater systemic stress than those without reduced stature; as such bioarcheologists have typically used stature as an indicator of overall health and stress during growth. Patterns of long bone growth in archaeological skeletal samples have been widely used as a proxy for comparing health and stress statuses between and among populations" (Agarwal 2016:133). The use of life course theory links the human skeleton to culture and social structure in many ways but would not be possible without embodiment theory.

Harris defines embodiment as, "a way of describing porous, visceral, felt, enlivened bodily experiences, in and with inhabited worlds" (Harris 2016:1). Embodiment theory is meant to show how the surrounding world influences an individual. Human bodies are formed by the environment. The stressors put on the body, both physically and mentally, strongly influence a person's growth and development. Humans grow and are active in their development through engagement with the social world. Those who have a poor, isolated, or conflicted relationship with their social world embody it. For example, low socioeconomic status (SES) reduces access to resources and can lead to malnourishment. This malnourishment can lead to several metabolic pathologies reflected in bone such as rickets, cribra orbitalia, osteoporosis, and enamel hypoplasia (Mariotti 2004). Lack of social engagement can lead to isolation, which decreases a chance of survival if a pathology occurs.

Culture and identity are embedded into an individual's body and impact the way a person lives. Experience and external variables create a person. Experiences shape perception, which may influence later decisions. As much as the world is shaped by humans, humans are equally shaped by the world they live in. Sofaer suggests that viewing a skeleton as a form of material culture crafted from lived experience “blurs the division of biological and social body” (Sofaer 2006:70). The body cannot exist without culture or society because human society influences everything a person needs to survive such as: diet, social bonds, and access to resources. Sofaer suggests analyzing skeletal remains and bony indicators, such as muscle markers, with a “humanistic focus” (Sofaer 2006:70) as past people are shaped by their lived experiences.

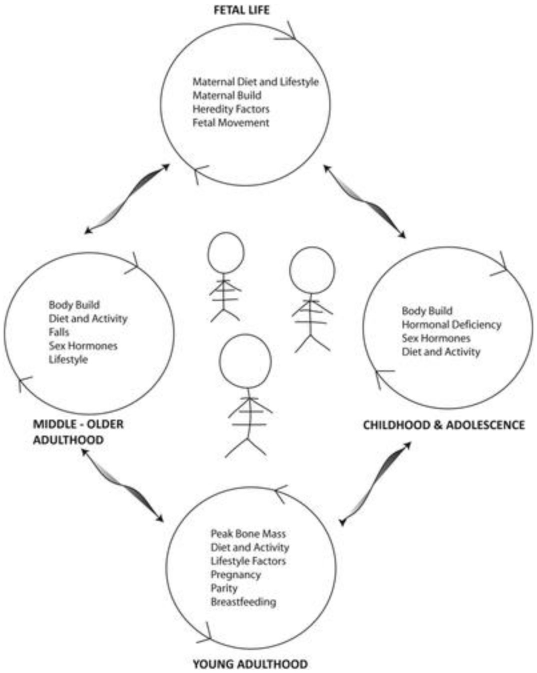


Figure 3: An Example of Life Course Theory displaying the impact of external factors on internal mechanisms. (Adapted from Agarwal 2016)

Embodiment theory connects an individual’s actions to their skeletal remains whereas life course theory is a collective view of how culture as a whole impacted an individual’s skeletal remains. By utilizing radiographs there is a potential to see a resemblance of the culture in which the people to whom these bones belonged, existed in. If a person has embodied their culture in ways that affected their diet, movement, or stress, it will be reflected in their skeletal remains.

Chapter three: Anatomy in Question

Tibia

The tibia is the larger of two bones in the leg. The tibia is responsible for supporting an individual's body weight and is an integral part of the knee and ankle joints. The tibia articulates with the femur, fibula, and talus bones. The medial malleolus stabilizes the ankle and provides insertion points for ligaments and muscles. The condyles on the proximal tibia support the femur and provide insertion points for the cruciate ligaments that articulate the knee (White, Folkens 2005:254).

There are several notable landmarks on the tibia. The medial and lateral condyles articulate with the condyles of the femur. In between those condyles is the intercondylar eminence where the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL) attaches to the tibia. The tibial tuberosity is a large oblong elevation on the proximal, anterior tibia, just below where the anterior surfaces of the lateral and medial tibial condyles end. The tibial tuberosity is the attachment site for the patellar ligament, which is a continuation of the distal tendon of the quadriceps femoris muscles (Drake 2009:25). Stress and strain on this tendon and ligament can lead to an increase in robusticity of the tibial tuberosity (White, Folkens, 2005:261).

Osteological change in an individual is dependent on external variables such as development, nutrition, environment, trauma, and activity experienced in a person’s life. The sex and stature of an individual can also influence the degree of osteological change and robusticity of the bone. The development of a muscle marker is explained by Wolff’s law: bone in a healthy person or animal will adapt to the loads under which it is placed. (Holt 2006:ii). However, the effect of the load on the bone is also subject to many of the variables previously mentioned. Holt explains that “every change in the form and function of bone or of their function alone is followed by certain definite changes in their internal architecture” (Holt 2006:i).

Physical activity affects both bone and muscle strength. Due to the plasticity and flexibility of bone, bone and muscle can change and adapt to the forces placed upon them, which influences the wear on ligaments and production of the bone. Bone’s effector cells (osteoblasts and osteoclasts) work to maintain homeostasis under the control of non-mechanical agents. Mechanical loads on bones deform or strain them, and larger loads cause bigger strains. Where strain exceeds the modeling threshold range, remodeling slowly increases bone strength to reduce later strains towards that range. As with past trauma such as a fracture, the bone develops a callous at the fracture site to strengthen the bone with the intention of preventing the fracture from occurring at that point again.

While the size of the tibial tuberosity is mostly affected by the activity performed by the quadriceps femoris muscles (Drake 2009:25), there have also been indications of sexual dimorphism. Muscle size is often larger in males due to the increased amounts of testosterone; however, males are generally more robust in size and stature compared to females. Males start puberty as late as two years after females so, although their growth potential does not have a longer duration, it does allow for the males to grow taller and bigger than females in that span of time. In addition to the delayed puberty, higher levels of testosterone increase muscle size, which increases bone size and creates a more robust skeleton (Drake 2009:13).

Hormonal effects and sexual dimorphism play a role in the extensiveness of muscle markers. William Bass explains that sexual dimorphism is “the biological and anatomical differences in size or appearance that occur between the sexes of animals” (Bass, 2005:48). Human males produce more testosterone, which contributes to a larger production of muscle, creating a more robust skeleton. Females are generally more gracile, and even though their muscle growth can be similar to men, the general size and stature of a female skeleton is smaller than a male.

M. Benjamin explains the size of human tibiae and the relationship between cross-sectional morphology and tissue-level mechanical properties. He writes,

> "Males and females showed nearly identical tissue-level mechanical properties. Both sexes also showed similar age-related degradation of mechanical properties and a similar relationship between cross-sectional morphology and tissue quality. However, for all body sizes, female tibiae were smaller relative to body size (i.e., less robust) compared to males. The results indicated that sex-specific growth patterns affected transverse bone size but did not affect tissue-level mechanical properties" (Benjamin 2006:21).

Although the bones of the males were larger, the tissue level mechanical properties did not suggest that the activity always dictated the size of the tibia; it influenced the degree of sexual dimorphism. Utilizing the tibia to identify morphological markers that may link to sexual dimorphism can greatly benefit osteological studies in bioarcheology.

Femur

The femur distally articulates with the tibia and the patella, and proximally articulates with the acetabulum, which is formed by the ilium, ischium, and the pubis. The femur is the longest and strongest bone in the body and supports all the body's weight for locomotion (White, Folkens 2005:255). The main function of the femur is weight bearing and gait stability. Due to its density, it is often recovered archeologically in a condition that makes it possible for analysis.

The proximal femur includes the head, neck, and greater/lesser trochanters. The head articulates with the acetabulum and operates as a ball and socket joint. At the center of the head there is a small ovoid depression called the fovea capitis and is the attachment site for the ligamentum teres (Chang 2019:1). Below the head is the neck; it is broader laterally than medially and angles 125-128 degrees depending on sex (Chang 2019:1). The proximal femur is described as having a “pyramid-shaped neck” that attaches the spherical head at the apex, with two bony protrusions. The greater and lesser trochanters attach muscles that allow the hip to move and are preceded by the cylindrical shaft at the base (Chang 2019:1). The trochanters allow leverage to the muscles that rotate on the ball and socket joint (Koch 1917: 210).

The shaft of the femur is slightly arched and is strengthened by a prominent longitudinal ridge called the linea aspera. The linea aspera is the rough crest on the posterior surface of the femoral shaft and thins inferiorly (White, Folkens 2005:15.1.4). The linea aspera is the muscle insertion for the adductor magnus and the vastus lateralis. The gluteus maximus inserts above and the short head of the biceps femoris originates below (Drake 2009:19).

The distal femur articulates with the tibia and the patella. It consists of two eminences known as the condyles which articulates with the tibial condyles. Above the condyles, sit the epicondyles. Koch writes, “The lateral epicondyle, smaller and less prominent than the medial, gives attachment to the fibular collateral ligament of the knee-joint. The medial epicondyle is a large convex eminence to which the tibial collateral ligament of the knee-joint is attached” (Koch 1917:211). The lower and posterior aspects of the articular surface articulate with the condyles of the tibia and menisci. These surfaces are separated by the intercondylar eminence (Koch 1917:211).

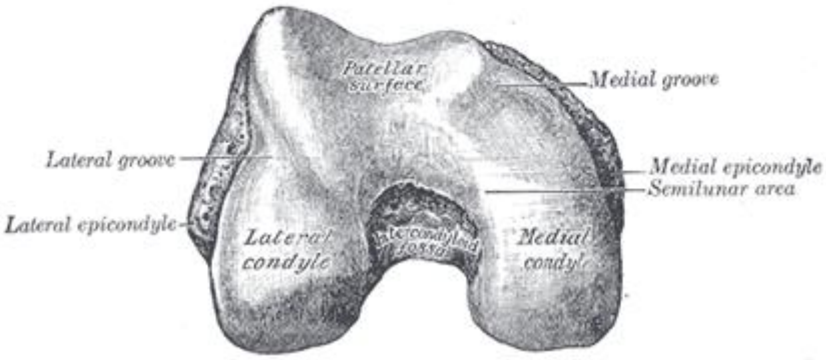


Figure 4: Diagram of the distal femur: Articulating surfaces including the condyles, epicondyles, and intercondylar eminence. (KOCH 1917)

Patella

The patella is a sesamoid bone; a bone embedded in a muscle or tendon that grows with biomechanical stress. Sesamoid bones are best defined as “skeletal elements that develop within a continuous band of regular dense connective tissue (tendon or ligament) adjacent to an articulation or joint” (Vickaryous & Olson, 2007:3).

Sesamoid bones develop in response to mechanical loads, and the patella had been shown to reflect habits such as digging or running (Samuels 2017:1). It is usually proportional to the individuals body size including stature and muscle growth. As the tendon wears on the bone, it grows larger so the increase in age would correlate to an increase in length. The patella is a lever system responsible for resisting gravity (Samuels 2017:1).

Chapter four: Materials and Methods

Materials

This sample originally included 130 radiographs. Nine radiographs were removed due to surgical alterations or ambiguous/ blurry details making it difficult to obtain measurements from the image. The new sample size consisted of 121 radiographs of knees from 75 females and 46 males. This sample was provided by a clinic that practiced general medicine. The radiographs were taken between the years 2014 and 2016 and were stored in a database within the clinic. The specific radiographs were chosen based on access and consent provided by the patients and the clinic. The necessity of medical imaging suggested an underlying medical issue or possible pain belonging to each individual. Medical history was not disclosed, so information regarding any pathology outside what is visible in the radiograph is unknown. The information disclosed included: sex, age, and side. This information was not visible when the measurements were taken, ensuring a blind test obscuring bias.

Sample Distribution

The sample of individuals (n=121) included in this study consisted of 75 females and 46 males who required the use of a radiograph between the years 2014 and 2016. The radiographs were taken at Greater Milwaukee Health Services in Wauwatosa, Wisconsin. The age ranged between 21 and 81 years averaging 51 years for both male and female. Of the 121 radiographs, 56 consisted of right knees and 65 were left knees (table 1). The radiographs selected were analyzed to determine the osteological variations and measure robusticity visible in a knee.

Table 1: Distribution of Tibial Radiograph Sidedness by Sex

	Right	Left
Female	35	40
Male	21	25

Table 1

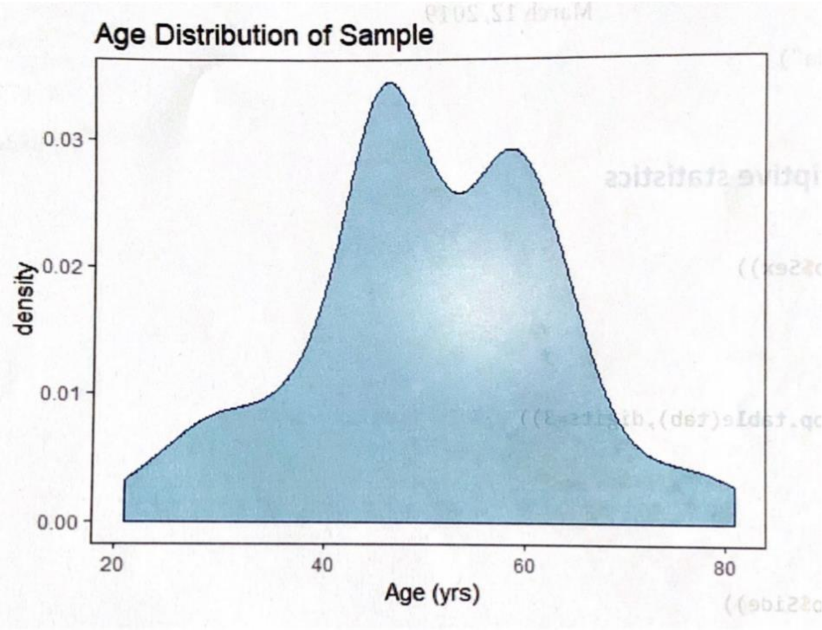


Figure 5 Age Distribution

Table 2: Age Distribution within the sample

Age	Number of Individuals
20-25	4
25-31	7
31-37	4
37-43	9
43-49	37
49-55	12
55-61	24
61-67	15
67-73	4
73-79	3
79-85	2

Table 2

Data Collection and Statistical Methodology

Measurements were analyzed to note variations or similarities found in and around the tibial tuberosity, an insertion point located below the condyles of the tibia. There were 27 measurements done on each radiograph. The measurements were done to outline the areas that included the greatest number of landmarks and to give ratios when statistically comparing the sample.

Tibial measurements included: the anterior and posterior distal/medial/proximal cortical width of the tibial shaft (at, above, and below) the height of the tibial tuberosity, the anterior-posterior depth of the tibial shaft, the distance in height from midshaft to the tibial tuberosity taken at the most protruding point and the distance in height from the tibial tuberosity to the start of the tibial shaft below the tibial condyles, the distance from the top of the proximal posterior/anterior height measurement to the middle of the posterior/anterior condyle, the posterior/anterior depth of the tibial condyle, and the angle of the tibial tuberosity (measured with a protractor). Femoral measurements included: the anterior/posterior condylar height and the femoral depth. The patellar measurements included: the proximal and distal height of the posterior and anterior sides of the patella and the width of the proximal patella.

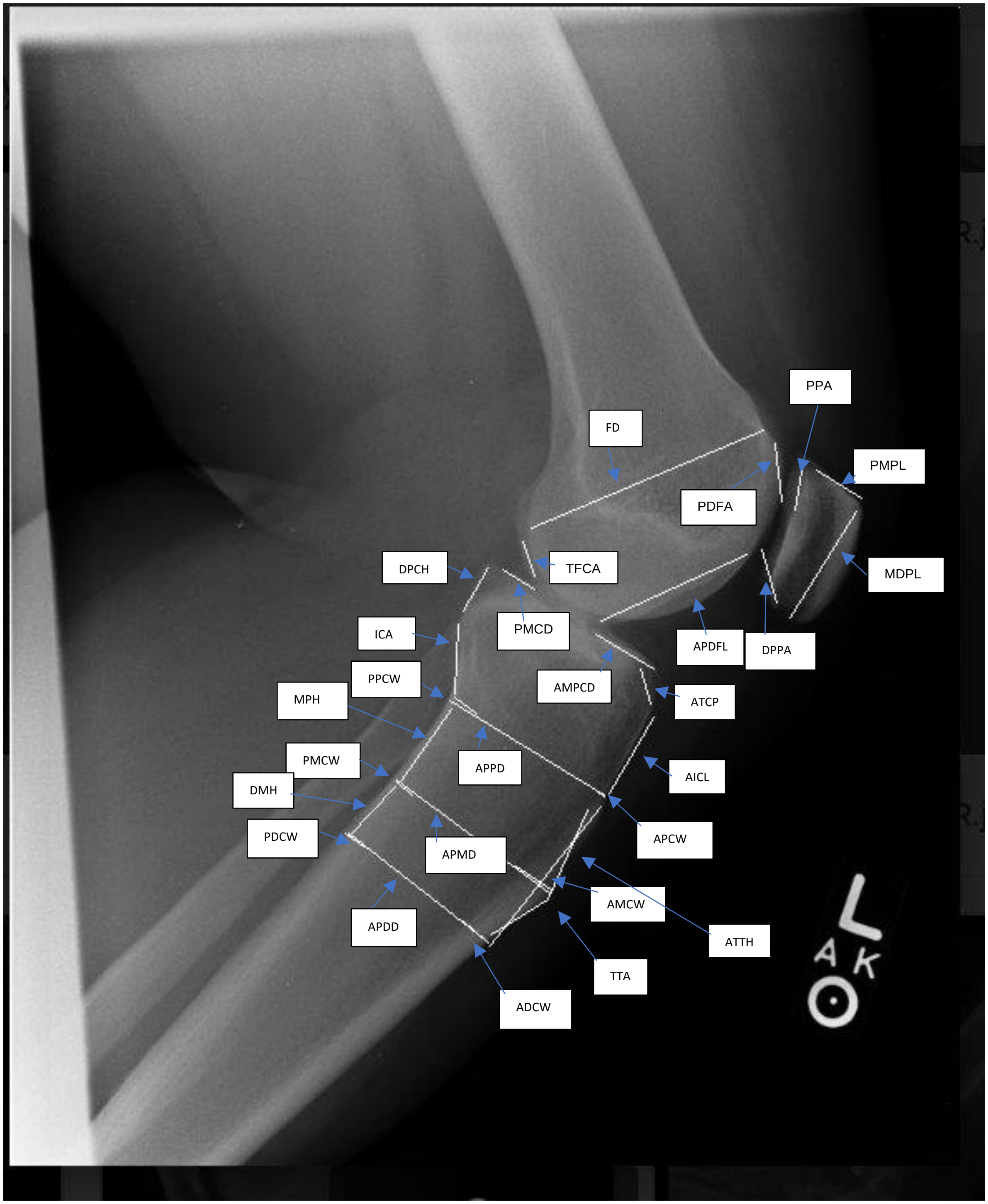


Figure 6 Diagram of Points taken on Radiograph of Knee

Table3: Abbreviation Meanings

Abbreviation	Meaning	Description
ADCW	Anterior Distal Cortical Width	Measurements taken at shaft beneath the tibial tuberosity where the thickness of the cortical bone regulates with the rest of the shaft. Measure the visible cortical bone thickness from front (lateral) to back (medial, where the cortical bone ends to where the spongey bone begins)
AMCW	Anterior Medial Cortical Width	Measurements taken at the most protruding point of the tibial tuberosity. Measure the visible cortical bone thickness from front (lateral) to back (medial, where the cortical bone ends to where the spongey bone begins)
APCW	Anterior Proximal Cortical Width	Measurements taken above the tibial tuberosity where cortical bone appears thinnest. Measure the visible cortical bone thickness from front (lateral) to back (medial, where the cortical bone ends to where the spongey bone begins)
PDCW	Posterior Distal Cortical Width	Measurements taken at shaft beneath and parallel to the tibial tuberosity where the thickness of the cortical bone regulates with the rest of the shaft. Measure the visible cortical bone thickness from front (lateral) to back (medial, where the cortical bone ends to where the spongey bone begins)
PMCW	Posterior Medial Cortical Width	Measurements taken parallel to the most protruding point of the tibial tuberosity. Measure the visible cortical bone thickness from front (lateral) to back (medial, where the cortical bone ends to where the spongey bone begins)

PPCW	Posterior Proximal Cortical Width	Measurements taken above and parallel to the tibial tuberosity where cortical bone appears thinnest. Measure the visible cortical bone thickness from front (lateral) to back (medial, where the cortical bone ends to where the spongey bone begins)
APDD	Anterior/Posterior Distal Depth	Width of the tibial shaft below the tibial tuberosity where the thickness of the cortical bone regulates with the rest of the shaft.
APMD	Anterior/Posterior Medial Depth (at tibial tuberosity)	Width of the tibial shaft at the most protruding point of the tibial tuberosity.
APPD	Anterior/Posterior Proximal Depth	Width of the tibial shaft from the front to the back above the tibial tuberosity, below the condyles.
DMH	Distal Medial Height	Distance from PDCW to the point below and parallel to the tibial tuberosity where the cortical bone regulates with the shaft to.
MPH	Medial Proximal Height	Distance between point at the tibial tuberosity to the point beneath the condyles with the thinnest amount cortical bone.
ICA	Inferior Condylar Angle	Where the top of the shaft widens and angles outward toward the articulating surface. Measurement from MPH to halfway up the condyle above shaft.
DPCH	Distal Proximal Condylar Height	Height from point where ICA regulates and meets articulating surface
PMCD	Posterior Medial Condylar Depth	Measurement from top of lateral condyle to intercondylar eminence.
TFCA	Tibial Femoral Condylar Angle	Angel from intercondylar eminence to the middle of femoral condyle.

FD	Femoral Depth	Width of femur from the midpoint up the femoral condyle on the back to the top of the femoral condyle on the front of the femur.
PDFA	Proximal Distal Femoral Angle	Top of the femoral condyle to the middle of the patella.
PPA	Proximal Patellar Angle	Middle of the patella to the top of the patella.
PMPL	Proximal Medial Patellar Length	Width of the patella at the top of the patella.
MDPL	Medial Distal Patellar Length	Distance from the top of the patella to bottom of patella.
DPPA	Distal Proximal Patellar Angle	Angle from bottom of patella to the back middle of patella.
APDFL	Anterior Proximal Distal Femoral Length	Angle from middle/front of femoral condyle to the intercondylar eminence.
AMPCD	Anterior Medial Proximal Condylar Depth	Distance from the intercondylar eminence to the front of the tibia on articulating surface.
ATCP	Anterior Tibial Condylar Protuberance	Angel from articulating surface to top/front of shaft of condyle
AICL	Anterior Inferior Condylar Length	Top/front of condyle to top of shaft
ATTH	Anterior Tibial Tuberosity Height	Top of shaft to tibial tuberosity
TTA	Tibial Tuberosity Angle	Angel of tibial tuberosity taken with protractor

This research focused primarily on the tibial tuberosity because it is a muscle insertion point for the quadricep femoris muscle and several ligaments that are essential for locomotion. The tibial condyles were measured due to the amount of strain and stress placed on the knee, which can cause wear at the joint both between the condyles and through the supports of the patella. The patella was measured because it anchors the landmarks together. The cortical width was measured to account for the muscle density that correlates to the density of the cortical bone, which would be a way to identify possible robusticity.

There were 130 radiographs acquired for this sample. Knees that had been surgically altered were removed to limit abnormalities. Each radiograph was numbered, and their sex and age placed in excel to perform a blind test. Blind tests were performed to remove any sort of bias towards the measurements.

Data were gathered by using a digital caliper on the printed radiographs and measured in millimeters (mm). The tibial tuberosity angle was measured with a protractor starting at the thinnest layer of cortical bone beneath the condyles to the most protruding point then to the distal point where the cortical bone returns to a density that matches the rest of the shaft.

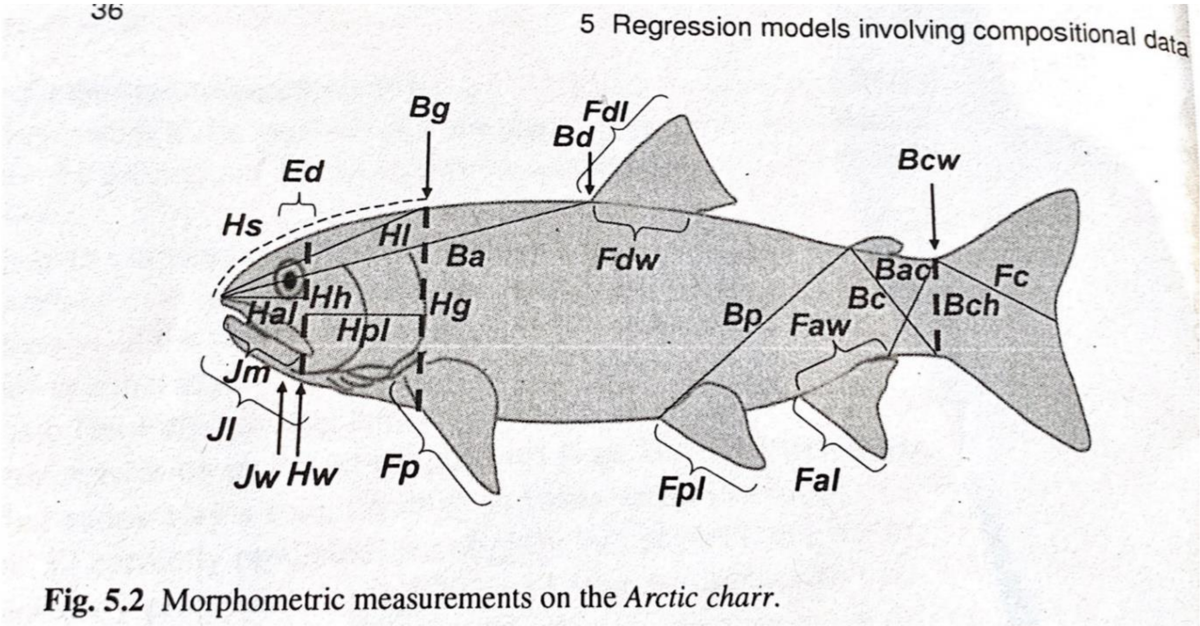
This data was statistically analyzed using a computer program, R. The program was utilized R to calculate the mean, standard deviation, regression models, log ratios, and predictive models. The type of analysis that produced the most effective outcome was the compositional data. To explain what compositional data is, Greenacre writes:

> "Compositional data are a special case in the field of statistics. They are non-negative data with the distinctive property that their values sum to a constant, usually one or 100%. They are measures of parts (or components) of some total, where the total is usually of no interest. Their special character is due to the fact that their values depend on the particular choice of parts constituting the total amount" (Greenacre 2018: 1).

Compositional data is a set of points logarithmically transformed into ratios used as a predictive model. Log ratios are made by measuring the frequencies of points that occur when predicting sex, age, or side. Greenacre writes,

> “What characterizes a set of compositional data is the constant sum constraint. Generally, it is supposed that this constant sum is one, even though the original data might be in hours, counts, or parts per million, for example. The operation of dividing out a set of data by its total to obtain the compositional values, which are proportions adding up to one, is called ‘closing the data’, or ‘closure’” (Greenacre 2018: 4).

Log ratios are useful in this research because the data set can serve as predictors to multiple variables. Greenacre uses fish morphology as an example. He took 26 morphometric measurements related to the mass, sex, and habitat. These measurements were not strictly compositional to begin with but, once they were expressed as proportions of their respective sums, computing the ratios worked the same on the original data as it would on the closed data.



36 5 Regression models involving compositional data

Fig. 5.2 Morphometric measurements on the *Arctic charr*.

Figure 7 Greenacre's Fish morphology: morphometric measurements

I used Greenacres’ work on fish morphology in a similar way when measuring this sample of tibias. Greenacre investigated whether the shape of the fish could predict sex by using logistic regression. As with the data from the present data, Greenacre found that log regressions did not produce high accuracy rates and used an alternative method. He writes, “An alternative is to use classification tree methodology (rpart function in R). Since the log-transformation is monotonically increasing, the cutoffs will be equivalent in the partitioning of the variables, transformed or untransformed, so the ratios can be left in their original scale." (Greenacre 2018: 37) This method removed the necessity for the radiographs to have been taken at the same scale.

The present sample was divided into two sets: a training set and a testing set. There were 90 cases in the training set and 30 cases in the testing set. The testing set was done with measurements outside the training model. This is done to avoid overfitting. Overfitting explains that one can only predict the sample that is used to make the test. Any tests outside the sample will be less accurate. Because the training sample was used to make the test, it will be more accurate as it is formatted specifically for the data in the sample.

From these sets, regression models were used on the training sample to see which measurements were most significant. Regression models and predictive models were performed on the testing sample using variables such as: age, side, and sex. The regression models produced less accurate results, so predictive models were used instead. The most useful predictive model was a decision tree called Classification and Regression trees (CART). CART models require a decision tree to identify the ratio of specific points and see if they are greater than or less than the value on the tree. If they are less to or equal to the value, they are female. If they are greater than the value, then one finds the value of the next ratio.

These ratios were formed into predictions. Although the accuracy was not very high in the testing sample, it is likely that the use of other remains to help determine sex would increase the accuracy of the sex identification.

The original objective of this project was to determine size variables between the sexes in this population. Measurements surrounding the condyles of the femur and tibia and the patella were taken to create ratios to see if any were sexually dimorphic and could indicate sex from the radiograph. Throughout all populations, males average larger than females. While this aids in sex identification, especially when the pelvis and skull are absent, it requires a large sample to compare in analysis. The statistical analysis from this sample found that using shape to identify sex was more accurate and did not depend on population identification to positively identify sex. Utilizing shape to identify sex only requires the condyles to be intact.

The use of the radiographs in this research is contained to the anthropology department at the University of Wisconsin Milwaukee. While professors do have access to these images, the anonymity of these prints is maintained. The only information provided is the age, sex, and clinic where the radiographs originated.

Chapter five: Results

Statistical Analysis

Points that correlated with the size of the tibia exemplified instances sexual dimorphism. The width of the cortical bone density was significantly larger in males. This is due to the degree of muscular hypertrophy caused by the greater amount of testosterone produced by males compared to females. The height of the tibia and the patella were larger in males. The width of the condyles, tibial shaft, and femoral condyles were also larger in males. The sample regularly met the hypothesis that the males would present with higher robusticity and be sexually dimorphic in size.

While this is important and can be helpful in identification of sex within samples, it is not consistent in samples outside of this population. One needs to have access to a large sample from the same population for the results to be accurate. It is well known that males are more robust than females, so it is less productive to provide a sample displaying evidence that the knee shows higher robusticity in males.

Therefore, I have decided to focus on shape rather than size. The measurements differ by size and side. Shape had an 80% accuracy in training set and 70% in the testing set. Side had an 86% accuracy in training set and 76% in the testing set. Although side identification was more accurate, it is less important to identify in a sample. The sample was divided to avoid overfitting, a statistical reality that shows that outside of the training sample, the results are not as accurate because the compositional data is made of similar measurements and outside samples are composed of different, non-correlated data.

Training and testing sets were utilized in this project, which split the sample into 75% training and 25% testing. The split kept sex in relative proportions. The measurements for this sample included an angle done to measure the tibial tuberosity. This was removed and analyzed separately because it did not provide productive information in predicting sex. The measurements were added together to create a compositional data set allowing us to measure points using log ratios when predicting sex, side, or age. There were 26 variables and 325 log ratios within each radiograph. These variables were used to see which ratio would predict sex best. The measurements did not provide accurate information in predicting age so it was determined that the points would be used to predict sex.

Once divided, it was determined which log ratios best predicted sex in the training set and attempted predictive models with Classification and Regression Tree (CART) models. To do this, the Train and Test log ratios from lists to data frames had to be converted.

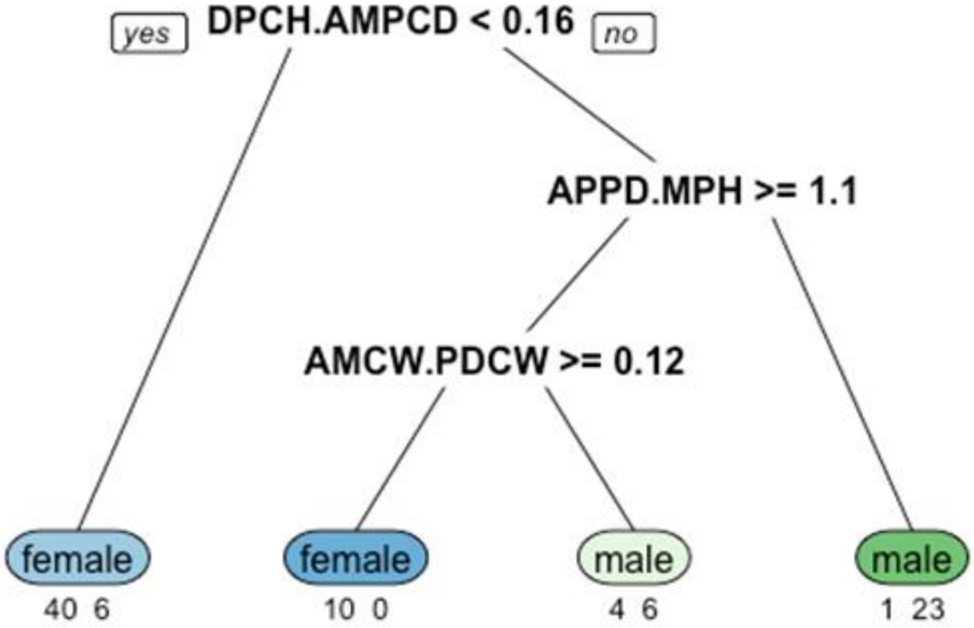


Figure 8 CART model analysis identifying frequencies of points that identified sex within sample

The classification tree results in a higher accuracy of 87.78% and uses only three of the log ratios. Here is how to read the plot:

2. If log(DPCH/AMPCD) is less than 0.16, then predict Female. Out of 46 cases where the log ratio was under 0.16, 40 were females. There were six cases of males who were incorrectly predicted as female.

3. If log(DPCH/AMPCD) is equal to or greater than 0.16, examine the log(APPD/MPH) ratio:

   - If log(DPCH/AMPCD) is less than 1.1, then predict male. Out of 24 cases in this state, 23 were actually males. There was 1 female incorrectly predicted as male.

   - If log(DPCH/AMPCD) is equal to or greater than 0.16 AND log(DPCH/AMPCD) is greater than or equal to 1.1, then examine log(AMCW/PDCW):

4. If log(AMCW/PDCW) is equal to or greater than 0.12, predict female. Each of the 10 cases in this situation were female.

   - If log(AMCW/PDCW) is less than 0.12, predict male. Of the 10 cases in this situation, 6 were male. Four females were incorrectly predicted as male.

When attempted, the testing set resulted in 70% accuracy. As expected, the tree does not do as well in the test data (accuracy falls from 87.78% to 70.00%). Still, this is an improvement over guessing the most common category (female, 53.33%). These three log ratios will help predict sex, but there is a lot of error.

Results

To identify the degree of sexual dimorphism in the sample, the data was analyzed testing male and female means, standard deviations, and t-tests. The chart below lists the results and describes the statistical significance. If the p-value is above 0.05% then there was no significance.

	F Mean	F SD	M Mean	M SD	t	p
ADCW	6.140	1.980	8.540	2.760	-5.230	0.000
AMCW	6.800	2.110	9.130	3.050	-4.630	0.000

	F Mean	F SD	M Mean	M SD	t	p
APCW	3.530	1.600	5.270	3.150	-3.580	0.001
PDCW	5.680	1.780	7.800	2.310	-5.390	0.000
PMCW	6.000	2.560	7.260	2.760	-2.520	0.013
PPCW	5.420	3.000	6.700	3.500	-2.080	0.041
APDD	34.280	3.320	40.500	3.510	-9.750	0.000
APMD	37.580	3.810	43.660	3.750	-8.670	0.000
APPD	37.480	3.560	44.240	3.960	-9.590	0.000
DMH	12.540	4.290	14.090	5.350	-1.690	0.094
MPH	12.520	4.820	17.990	7.590	-4.460	0.000
ICA	14.670	3.130	18.360	4.790	-4.730	0.000
DPCH	12.880	2.530	16.540	2.810	-7.290	0.000
PMCD	12.100	3.030	14.300	3.140	-3.830	0.000
TFCA	8.680	4.100	9.580	4.010	-1.200	0.234
FD	55.190	4.950	62.310	4.640	-8.030	0.000
PDFA	9.780	3.730	11.910	3.910	-2.990	0.004
PPA	8.370	3.640	10.750	4.140	-3.240	0.002
PMPL	15.700	2.600	18.340	2.290	-5.860	0.000
MDPL	29.870	3.050	36.350	7.110	-6.010	0.000
DPPA	14.010	3.080	16.850	3.820	-4.320	0.000
APDFL	29.530	5.230	32.560	7.190	-2.520	0.013
AMPCD	14.670	3.800	13.470	4.040	1.650	0.103
ATCP	8.880	2.880	9.090	2.600	-0.430	0.671
AICL	13.440	4.090	16.320	5.770	-3.010	0.004
ATTH	29.000	5.300	36.260	7.720	-5.720	0.000
TTA	137.240	10.420	139.270	14.150	-0.850	0.395

F = Females, M = Males; p values for two-tailed tests

Figure 9: Mean, SD, and P-value chart

The sample was generally sexually dimorphic with the points from the males being larger than the females in all measurements but AMPCD, which was larger in females but not statistically significant. This is helpful in determining sex when one is able to compare the data within the sample. Size dimorphism provides some insight for determining individual sex, but is not a fully sensitive or specific measure, so shape was incorporated into the study as well. With this knowledge, the focus shifted to use the shape of the tibia to possibly identify differences in the sex of the individual. The shape of the condyles, the tibial shaft, and the density of the tibial cortical bone width were utilized in sex identification and can be labeled as sexually dimorphic. The way to determine sex statistically was through a classification and regression tree (CART) model. CART models are decision trees utilized as a predictive model.

The log ratios selected show that the Distal Proximal Condylar Height (DPCH) and the Anterior Medial Proximal Condylar Depth (AMPCD) indicate shape is sexually dimorphic. Anterior/Posterior Proximal Depth (APPD) and Medial Proximal Height of the tibia (MPH) indicate size and shape of the tibia can indicate sex and the cortical density varies by sex due to muscular hypertrophy.

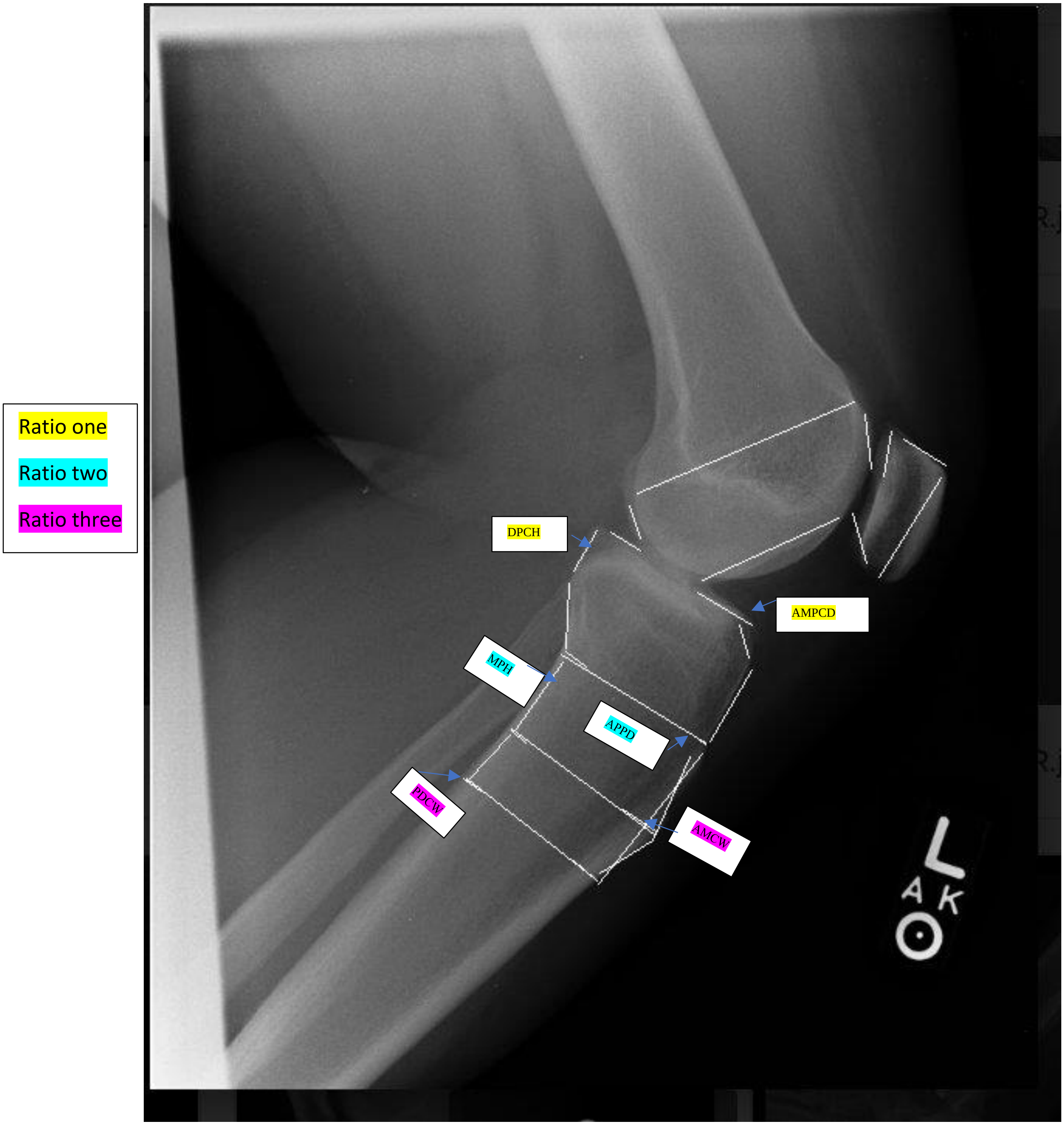


Figure 10 Diagram of Points taken on Radiograph of Knee including only the ratios utilized in the CART procedure

Chapter six: Conclusion

Conclusion

Insights gained from this research demonstrate the benefits of utilizing the shape of the tibia in sex identification of skeletal remains. In comparison to Toon's research which, utilized geometric morphometric and discriminant function analysis on skeletal remains to form their conclusions, I used compositional data on a radiographic image of the knee. My data resulted in the same amount of accuracy (70%); however, it only required three ratios, whereas Toon's research included 21 landmarks (Toon, 2014: 27) to get the same amount of data. Toon used three types of analysis to ensure that the only points measured analyzed shape. Toon excluded size and orientation by using generalized Procrustes analysis and Kendall's shape space where only shape data exists. (Toon, 2014: 33) I did not go to these measures to exclude size, however, as my data was already digitized, it might not have been necessary.

The questions addressed in this research addressed were:

1. "Is the shape and size of the knee sexually dimorphic?"
2. "Can one use the size and shape of a knee as a contribution to the identification of the sex of an individual from a radiograph?"

The answer to the first question is yes, the shape and size of the knee is sexually dimorphic. However, size is less consistent throughout populations, so it is important to identify if the remains are from the same place of origin before comparing size variants. The answer to the second question is also yes, the use of the shape and size of an individual can be used as a contribution to a sex identification of an individual through a radiograph. Ideally, one would only need a single to knee to account for the ratios and input them into the CART model to discover the sex of that individual.

There were three factors within the sample that contributed to the analysis of the knee including: the tibial and femoral condyles, the height and width of the tibial shaft, and the tibial cortical density. The cortical density was affected by the degree of stress/strain put on the bone as well as the amount of muscular hypertrophy that existed around the bone. It is acknowledged that the sample size was limited, and the sex was not divided equally. A larger sample size may indicate possible patterns between the variables.

There was a clear correlation between age and the size of the tibial tuberosity. The angle measurement decreased as the age increased (Appendix A). The tibial tuberosity angle was not affected by size or sex. The condyles were a contributing factor of sex varying in size and shape. The patella did not provide any information that assisted in possible sex estimation. It was expected that the shift in hormones that decreases amounts of estrogen during menopause would influence the size of the tuberosity and cortical width and present evidence that females with increased age would result in a smaller tibial tuberosity and with smaller cortical bone density. Although the size of the tibial tuberosity did decrease with age, this was not consistent among a specific sex. This study produced one primary result with several supporting observations that may benefit future studies of biological anthropology.

The primary result recovered was the variance in shape and size of the tibia and how that can contribute to the identification of sex within an individual. Sexual dimorphism in other areas was present and may contribute to further sex identification in samples displayed in radiographs. This research also resulted in the ability to identify sex and age from compositional measurements. Ideally, this would allow for an anthropologist to measure a set of radiographs from their own sample, enter them into the CART model and identify the sex of that knee with

70% accuracy. While 70% is not highly accurate, with other information gathered from the rest of the skeleton, it can contribute to a more holistic identification of the sex of that individual.

The original hypothesis regarding sexual dimorphism in the tibial tuberosity and patella was that the width and height would be consistently larger throughout the male knees. The tibial tuberosity is usually equivalent to the body's height and weight and it grew accordingly; there were not many signs of extreme robusticity in males or females. There were too many variables that influenced the skeleton to determine the occupation or amount of activity performed by an individual based on the landmarks recovered in a radiograph.

This research could benefit anthropology by providing methods to analyze sex from measurements done on radiographs. Radiographs are cheap and accessible, and the tibia is one of the most sustainable bones when recovered archaeologically due to its bone density, which increases the opportunity for use of this project. This research concluded that sexual dimorphism effects the shape and size of the proximal tibia and it has a 70% accuracy rate of identifying sex from a radiograph.

Ultimately, the information displayed in these radiographs may help recover sex and age of the individual based on the shape of the tibia, the robusticity of the tibial tuberosity, and the general rugosity of the patella to estimate age. Finally, it is hoped that this research provides a useful step towards methods utilizing radiographs to help determine accurate, quantifiable methods to help identify sex in a sample within biological anthropology.

Next Steps and Future Research

Future aims for this research and further application of these methods could contribute to the variation of tibial shape between sexes seen in radiographs, how age and the application of Wolff's law affects the development of the tibial tuberosity, and how this compositional data can contribute to future samples. Two extensions of the present study are required before its usefulness to forensic anthropologists and archaeologists can be evaluated. First, it must be established whether the log-ratios that identified as useful in predicting sex by the CART procedure are consistent across populations. Second, the log-ratios need to be validated as useful when used to analyze actual, physical skeletal remains. This could be done by using a sample of remains whose sex has already been identified, taking the six measurements on the available tibiae, and see if the results are consistent with this project. If they are, the CART model would be useful for in-field techniques.

While this thesis adds to research on shape analysis of the tibia and how it can influence sex identification, it did not provide a *more* accurate method of doing so. The next step for this research would be to test this information on a set of skeletal remains with known sex. On this set of remains, one can measure the angles for log ratios and compare accuracy rates. Ideally, this research would be most useful in analyzing archeological remains.

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Appendix: TTA Measurements and Age

While most of the ratios were only productive in predicting sex, the tibial tuberosity was useful in predicting age. When predicting sex and age it was divided into 91 training cases and 29 testing sets. There were 54 females and 37 males in the training set and 17 females and 12 males in the testing set. The training set mean age was 50.49 years old with a standard deviation of 12.47. The testing set mean age was 53.13 with a standard deviation of 12.53.

Since the tibial tuberosity angle (TTA) was excluded in the earlier analysis, a separate test was done to analyze the relevance of these points. The t-test suggested that the TTA did not provide a significant difference for the sexes. This suggested that a logistic regression predicting sex from TTA would not be very successful. The log regression consistently predicted the most frequent class: Female. Sex was not a probable variable to be identified when using the tibial tuberosity angle.

Age, however, does predict TTA, with older people having a lower TTA angle than younger people. The model is statistically significant F(1,89) = 34.78, p value = 0.6.511e-08: $\widehat{TTA} = 162.99 - 0.51 * \text{Age}$ and indicates that as a person ages, the angle is predicted to decrease. The multiple R-squared value indicates that age explains about 28.10% of the variation in TTA. This is fairly high. The root mean squared error for the training equation was then calculated. This is:

$$\mathbf{RMSE} = \sqrt{\frac{(y_i - \hat{y}_i)^2}{n}}$$

Figure 11 calculation of root mean squared error for training equation

The RMSE for the training data is 10.19 and the RMSE for the test data is 14.04. When the equation was used to predict the test data, the root mean squatted error increased from 10.17 to 14.04.

The angle of the tibial tuberosity could not provide sufficient data regarding the sex or the side of knee, however, it indicated that as a person ages, the angle of the tibial tuberosity decreases. This may be due to the increase of surrounding cortical bone or the decrease in correlating muscle mass from the quadricep femoris muscles.

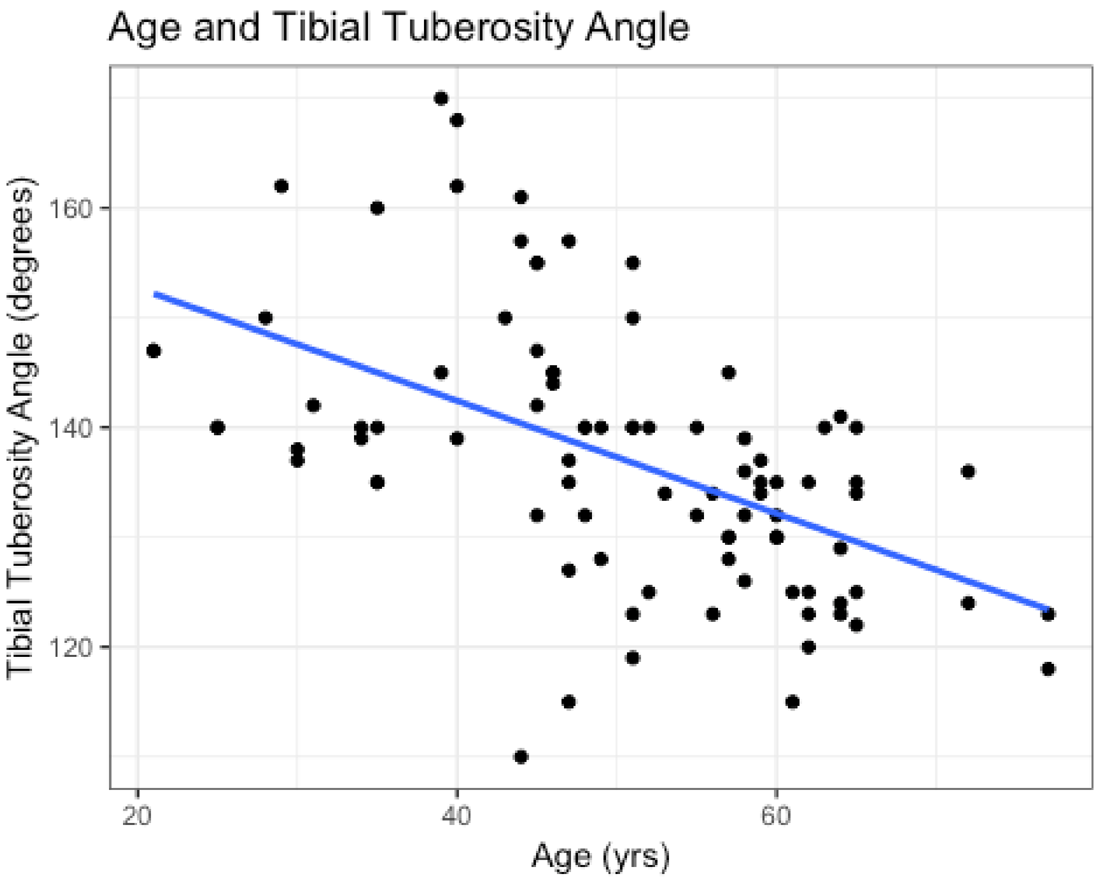

Figure 12 Graph of Age by Tibial Tuberosity Angle