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An Exploration of the Correlation Between Body Mass and Skeletal Measurements of the Long Bone Joints and Diaphyses

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An Exploration of the Correlation Between Body Mass and Skeletal Measurements of the Long Bone Joints and Diaphyses

by

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ABSTRACT

Body mass is a characteristic of the human body that can aid in narrowing down potential identifications of unidentified individuals. However, when faced with skeletal remains, body mass is not easily ascertained, especially when the remains are incomplete. This research explores the potential correlation between body mass and long bone dimensions in order to aid in identification efforts. The limited research done prior has been conducted almost exclusively on the lower limbs—therefore, one of the primary foci of this study is to assess the efficacy of using the joint surfaces and shaft measurements of the upper limbs.

Five long bones (humerus, radius, ulna, tibia, and femur) were measured across a sample size of 20 males of varying body mass from the William M. Bass Skeletal Collection at the University of Tennessee Knoxville. Fifty-one measurements assessing joint surface area as well as shaft diameters were taken directly from the remains, while three more were extracted from the existing data. Descriptive analysis showed promising results for a potential correlation between body mass and certain measurements of the long bones. The significant correlations were largely evenly distributed among the articular and diaphyseal surfaces. The lower limb, especially the shaft diameters, was found to be more highly correlated with body mass values. The upper limb, however, showed much more limited potential for estimating body mass, likely since it is not directly involved in carrying weight. These findings have implications for further studies with larger sample sizes.

Keywords**:** BMI, long bones, skeletal measurements, unidentified remains, joint surfaces, human osteology

DEDICATION

To the unidentified persons of the world—may you rest knowing someone is looking for you.

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LIST OF ABBREVIATIONS

AP	Anterior-Posterior
BJS	Bureau of Justice Statistics
BMI	Body Mass Index
CDC	Center for Disease Prevention and Control
DNA	Deoxyribonucleic Acid
ME/C	Medical Examiner/Coroner
ML	Medial-Lateral
SD	Standard Deviation
UTK	University of Tennessee Knoxville

CHAPTER I: INTRODUCTION

As of 2018, there were known to be 11,380 sets of unidentified remains at coroners and medical examiners' offices (Brooks 2021). This is not only devastating to the potential relatives and loved ones of the unidentified person but also creates a backlog of cases for law enforcement agencies. Many law enforcement agencies lack the necessary resources to continue pursuing cases that are without leads or have "gone cold" which may result in these cases being untouched for years (Heurich 2008). To prevent such a backlog, it is important to gain as much identifying information about discovered remains as soon as possible in order to work towards a positive identification.

If remains are found soon after the death of the individual, there are many more identifying characteristics available to investigators. These include fingerprints, deoxyribonucleic acid (DNA), physical features such as stature, and modifications such as tattoos or scarring. However, remains are occasionally found in the skeletal state which adds difficulty to the identification process. There are many estimations that can be obtained through the use of anthropological methods, including age, stature, and biological sex of the individual. However, these elements alone may not be enough to narrow down a successful identification. For this reason, research is constantly expanding the body of knowledge on the impact of lifestyle on the skeleton. (Sheng et al. 2021). One such example is analyzing the impact of body mass on the skeleton, specifically on the joint surfaces (Harrington 2013).

As humans go about their daily lives, the skeleton works to support the body and assists in the induction of movement. While these processes occur, the skeleton is supporting the body mass of the individual. Body mass has been shown to impact the skeleton in a variety of ways, including a positive association between obesity and osteoarthritis of the lower limbs ("Obesity Prevention Source"). Muscle attachments occur primarily at joint surfaces, meaning that the use of the musculoskeletal system to both support and carry weight can cause physiological changes to the joint surfaces (Simkins 2018). For example, Wolff's law, developed by Julius Wolff, states that bone adapts to the stress put on it by weight-bearing motion. It can therefore be inferred that differing body masses would have differing effects on the joint surfaces and on the bone as a whole.

This inference has been explored on a limited basis by previous research, but this research primarily focused on the lower limbs, as those are the primary bearers of mass for the human body (Simkins 2018). Some of this research found suggestive results indicating a relationship between obesity and dimensions of the femur and tibia but did not explore the upper limbs in any way (Harrington 2013). However, it is possible that at times the lower limb bones will not be recovered, meaning only upper limb bones are available. The purpose of the research conducted and presented here aims to fill the gap of knowledge as to the impact of body mass on the long bones with the inclusion of and focus on the bones of the upper limbs. Since the upper limbs are components of movement, such as execution of gross and fine motor skills, it can be reasoned that body mass also affects these bones, something which has not yet been explored in depth.

Benefits of this research are two-fold. Primarily, this research explores a correlation that could potentially be extracted and utilized to infer a range of potential body masses from only skeletal measurements. A correlation, if found, could aid in creating a potential range of body mass for an unidentified individual, which when combined with other anthropological information, could lead an investigation closer to a positive identification. Secondarily, exploration of the potential correlation between body mass and skeletal measurements allows for research that has impact on not only anthropology and forensic science, but also for medical professionals and diagnostic care. The null hypothesis, H_0, for this study is that there will be no correlation between body mass and skeletal measurements of the long bones. The proposed alternative hypotheses are as follows:

H_1: There is significant correlation between body mass and articular surface size of the long bones.

H_{1a} The correlation is present in both the long bones of the upper and lower limbs, but stronger in the lower limbs.

H_2: There is a significant correlation between body mass and diaphyseal diameters of the long bones.

H_{2a}: The correlation is present in both the long bones of the upper and lower limbs, but stronger in the lower limbs.

H_3: The diaphyseal diameter size of the long bones will have stronger correlation to body mass than the articular surfaces.

CHAPTER II: LITERATURE REVIEW

The topic discussed in this research is multi-faceted, with several factors to consider in approach to the problem. Therefore, previous studies must be reviewed in a multi-faceted manner as well. The issue of correlation between body mass and the skeletal long bones has therefore been divided into sections for this chapter, with literature pertinent to each section being addressed accordingly. These sections are as follows: unidentified remains, identification processes, body mass index, estimation of body mass from skeletal remains, and body mass and the joints.

Unidentified Remains

While there is no internationally recognized definition for unidentified remains, such can be loosely defined as human remains not identifiable to a known person. This variability in definition can lead to lack of data surrounding the true problem of lack of identification (Reid et al. 2023) and create ambiguity in discussion on the topic. Lack of identification creates several barriers to both medicolegal and social processes. In the medicolegal realm, lack of identification halts investigation into cause and manner of death, as well as hindering a criminal investigation if one is necessary. Socially, lack of identification of remains means that families and loved ones of the decedent may not be able to properly grieve loss, as they may not be aware their loved one is deceased. Furthermore, identification is necessary in order for a death certificate to be completed, a key step in end-of-life processes such as release of life insurance, control of assets and liabilities, and more (Reid et al. 2023).

Data on unidentified remains can be hard to collect, as the true number of remains is unknown. This is due simply to the fact that not all sets of remains—whether they will be identified or not—have been discovered at the time of any publication or research. On any given day, there are thousands of active missing persons cases in the United States (NamUs). Each of these missing individuals has the chance of being deceased. Out of those that are deceased, not every set of remains will be discovered, and out of the discovered sets, not every one will receive a positive identification. Therefore, much of the quantifying data surrounding unidentified remains must be gathered in a controlled environment. In this circumstance, controlled environments refer to medicolegal facilities such as medical examiners' and coroners' (ME/C) offices.

Beginning in 2004, the Bureau of Justice Statistics implemented a census to be conducted within ME/C offices. This census was designed to provide data on the "personnel, budgets, and workload of medical examiner and coroner offices by type of office and size of jurisdiction" as well as the population of unidentified human remains that each office works with (Bureau of Justice Statistics [BJS] "Medical Examiner and Coroner Offices, 2004). To date, two censuses have been conducted (in 2004 and 2018) with both available on the Bureau of Justice Statistics database. These censuses provide a wealth of information regarding operations of ME/C offices as a whole, but the most significant data for this research is that pertaining to unidentified remains.

In 2004, it was reported that there were 13,486 unidentified decedents on record across 1,998 offices. Roughly 23% of these offices had more than one unidentified decedent at time of survey, with the New York, NY, office having a remarkable 3,612 unidentified decedents on record (roughly a quarter of all unidentified decedents). The survey posited that roughly 4,400 unidentified remains are reported each calendar year, with 25% remaining unidentified after a year has passed. Out of those, approximately 600 are brought to final disposition (burial, cremation, or other methods). Of the offices surveyed, only half were reported to have a policy regarding retention of records for unidentified remains (Hickman et al. 2007). This data reflects the immensity of the issue of unidentified remains, as it illustrates that a substantial number of cases either do not reach resolution after time has passed or are not continued to be held by ME/C offices.

The 2018 census of ME/C offices utilized slightly different reporting measures—for example, no data was submitted in regards to the number of cases retained after one year. However, data was included regarding the percentage of cases in which deoxyribonucleic acid (DNA) evidence was collected. The 2018 census report found that there were 11,380 unidentified remains cases among the 2,040 offices surveyed. This was a decrease of 2,106 cases with an additional 42 offices surveyed from 2004. Of these cases, fewer than half had collected and recorded DNA evidence (Brooks 2021). This parallels the 2004 findings regarding record retention for unidentified remains, indicating a persisting lack of continuity for unidentified remains cases. The question of whether this is due to lack of personnel, resources, funding, or other issues is dependent on the office in question as well as the complexity of the cases.

Another barrier to identification occurs in the underreporting of the presence of remains outside of an office's jurisdiction. While national databases exist, such as the National Crime Information Center or the National Missing and Unidentified Persons System, use of these systems may not be required by local law enforcement. Besides use of national systems, the presence of unidentified remains is not always reported across jurisdictions. If a decedent had traveled across multiple local or state jurisdictions prior to their death, this lack of communication can cloud the identification efforts by ME/C offices. Improved communication and reporting are initiatives that can greatly improve identification efforts, therefore reducing the amount of unidentified remains.

Identification Processes

While procedures for identifying human remains depend on the standard operating procedures of individual agencies, there are common practices found throughout medicolegal facilities. When remains are found prior to entering stages of decomposition, visual identification may prove to be a satisfactory source of identification. This may come from showing photographs of the victim to potential family members, from matching the remains to a missing person's photo, or viewing of the remains by witnesses, family members, or other relevant personnel. Identification may also preliminarily be found in the form of photo identification such as a driver's license or state-issued ID, passport, or other such identification. However, these methods are not considered scientific, and can leave room for error (Prahlow 2010).

Scientific identification processes come in varying forms. Deoxyribonucleic acid (DNA) is often referred to as the "gold standard" of identification. DNA is often referenced as the blueprint of life, as it contains the genetic instructions necessary for function in the body. DNA is organized in pairings called base pairs. There are over three billion base pairs in the human genome, with the combination of base pairs different in every individual, excluding identical twins (Bukyya et al. 2021). This means that an individual's DNA can come from them and them alone, making DNA an extremely important source of identification. However, DNA comparison requires a known sample to be obtained for comparison with the collected sample. If there are no clues as to the individual's identity, it may be very difficult or impossible to obtain a known sample for comparison, resulting in lack of identification.

DNA can also be difficult to obtain and process, especially in the case of skeletal remains. DNA begins to degrade at the moment of death, with such death occurring in the soft tissues first. Extracting DNA from skeletal remains may be a challenge in and of itself, since the DNA requires mild modification to be processed. The process generally requires removal of contaminating DNA, pulverization of the skeletal material, and purification (Latham & Miller 2018). Even after these processes are complete, there may be little to no viable DNA for processing. This process can be time consuming, meaning a backlog of cases is formed (Nelson 2011). This backlog varies from jurisdiction to jurisdiction, and similar to regular case backlog, can be caused by lack of personnel, resources, funding, and other issues.

Another method of identification considered to be a "gold standard" is that of fingerprints. Similar to DNA, fingerprints are unique to each individual. Fingerprints are formed by raised ridges on the fingers consisting of pores and sweat glands (Kaushal & Kashual 2011). These are unique and unchanging, meaning they are ideal for use as an identification tool. However, similar to DNA, fingerprint comparison requires a known source. If a known source is unavailable, comparison cannot take place, and lack of identification may occur. Furthermore, for fingerprints to be obtained, the flesh must be present on the decedent. This means that in cases of skeletal remains, fingerprints are not necessarily a viable option for identification.

Useful in both skeletal and non-skeletal remains cases is dentition, or teeth, of the individual. Forensic odontology is a field dedicated to the use of teeth and oral structures to aid the in identification of individuals, as well as aid in forensic investigation as a whole (Krishan et al. 2015). Dental structures are the hardest structures in the body, and resist both decomposition and intense temperatures, such as those from fire. Furthermore, since teeth are unique to an individual, they are ideal for identification. This identification can be done through matching features of the dentition to antemortem records of individuals. Features that are often looked at include restoration and hardware (such as crowns, fillings, etc.), wear patterns, and pathologies of the tooth such as cavities (Krishan et al. 2015). Dentition offers several opportunities for identification, but similar to other methods discussed, there must be known records to compare the dentition to in order for identification to be made. However, dentition can provide clues as to age, sex, race/ethnicity, and other classifications that can assist in identification efforts (Krishan et al. 2015). This evidence is especially crucial as it transcends decomposition, while fingerprints and DNA may not.

Skeletal remains provide their own unique opportunities for scientific methods of identification. Forensic anthropology most often refers to a subspeciality within biological anthropology dealing with the study of human skeletal remains in a legal or medicolegal context (Ubelaker 2004). Forensic anthropology analysis is commonly used to create a biological profile, consisting of age, sex, ancestry, and stature. Age can be determined through the natural development of the skeleton, which begins in the fetal stages and progresses through adulthood. The progression of development in subadults can indicate range of age and is most commonly conducted with the long bones and teeth. Once growth is completed, observation of features on the pelvis and skull are most often employed, and at times multivariate analysis can be used (Getz 2020). Sex can be determined primarily by the pelvis. This is done by observing several factors related to the width of the pelvic opening, especially as it relates to birthing abilities in females—but features of robusticity on the skull and long bones also enjoy high reliability in sex estimation (Duric et al. 2005).

Ancestry is another facet of the biological profile, describing the ancestral background of an individual. Its meaning is often conflated with that of social race, causing debate on the efficacy of the inclusion of this parameter (Ross & Williams 2021). Common designations for ancestry include African, Asian, and European descent. This is most often quantified by the skull, with important details being the cheekbone projections, facial prognathism, nasal aperture shape, and tooth morphology. The final component, stature, can be determined with the long bones. Formulas utilized to calculate stature with measurements of these bones vary, making it more susceptible to variation. A common model used is linear regression, which plots the stature versus the bone or part in question. Stature is important in the narrowing down of the identification pool, and literature is confident with the ability to estimate stature (Krishan et al. 2011). With some components of the biological profile, databases such as Fordisc 3.0 (University of Tennessee-Knoxville) can provide estimations following entrance of skeletal measurement data. This makes a biological profile more accessible to departments that may not have access to a professional well-versed in making these estimations personally. Overall, the biological profile is a very consistent starting point for dealing with skeletal remains. However, even a biological profile can result in hundreds or thousands of potential matches.

Trauma and other pathologies discovered within the bones may assist with narrowing down potential matches. Trauma to the bone, pathologies associated with disease, and other individualized characteristics of the bone can be utilized as unique features, making them ideal for identification (Cunha 2006). In cases where previous disease, congenital abnormalities and characteristics, or healed injuries are present, there is opportunity for comparison with potential matches. This can be obtained in many ways, but a primary method is the use of medical records. For example, an unidentified individual discovered may show evidence of a healed fracture on the tibia. In the investigations process, potential matches can be narrowed by investigation into whether or not they had the same fracture. If x-rays of the potential match's fracture are available, those can be compared as well, further expanding the validity of the match (International Committee of the Red Cross 2013). However, these records are not always available, and when records are not available, similarities in trauma and pathologies may still not be enough to warrant a positive identification. Therefore, data other than the biological profile or the trauma and pathology of the bones may need to be extracted and analyzed. An example of such data may include body mass, the focal point of this study.

Body Mass Index (BMI)

One way to further narrow the number of potential matches is to consider the addition of body mass as a variable. An individual's body mass index, or BMI, is a calculation tailored to the individual's exact height and weight. BMI is calculated with the metric system by simply dividing the weight in kilograms by the height in meters squared. In the imperial system, commonly used in the United States by the general population, BMI is calculated by dividing weight in pounds by the height in inches squared, followed by multiplying by a conversion factor of 703. BMI is suggested for use by adults aged twenty and older. The overall range is nonspecific, though "levels" exist for diagnostic use. These levels are labeled as underweight, normal, overweight, and obese (Center for Disease Prevention and Control 2022).

BMI is most often used in clinical and diagnostic settings for identification of obesity and as a precluding factor for many health issues. Obesity is considered an epidemic both in the United States and globally. As of March 2020, roughly 41.9% of Americans were considered to be obese on a BMI scale (CDC 2022). Obesity is associated with several health issues, including but not limited to diabetes, hypertension, coronary heart disease, stroke, some cancers, and lower quality of life (CDC 2022). While BMI is a useful tool for patient care in that it allows for monitoring of risk factors, it can have other applications in forensic analysis.

BMI is indicated to be a definition of height and weight characteristics that allow for sorting of the human population into the pre-discussed levels (CDC 2022). It has also been determined that BMI can be influenced by age, sex, and ethnicity (Reas 2007), which have been stated to be part of the biological profile utilized by forensic anthropologists. Therefore, it can be postulated that body mass, in the form of BMI, can serve as a class characteristic for identification of remains. This would allow for further narrowing of possible matches to unidentified remains by acting as a potential exclusionary tool—if it is known that the decedent has a BMI of roughly 30.2, for example, a potential match with a BMI of 19.5 can likely be excluded.

However, the BMI system is not without drawbacks. Many critics of the BMI system express that BMI does not account for ratios of muscle mass, fat mass, and bone mass to one another or to the overall mass of an individual (Nuttall 2015). Therefore, two individuals with the same BMI could still have different body compositions resulting in different physiques. This is notable for a diagnostic setting, but has little implication on a potential forensic use. Regardless of body composition, the BMI calculated for a specific weight and height will be standard, meaning that it can still be compared to an unknown decedent's BMI. The primary drawback in this scenario is the calculation of BMI from the remains, specifically when the remains in question are skeletal in nature.

Estimation of Body Mass from Skeletal Remains

It is known that evaluating BMI from skeletal remains presents a unique challenge, as BMI is a measure of qualities no longer readily found in skeletal remains. However, research conducted shows promise for the use of estimating BMI from skeletal remains. The basis of the conducted research focuses on the impact that obesity can have on the structures of bone. Obesity has been found to impair bone strength resulting in possible disease and impaired function of bone metabolism, but the most influence is exacted through mechanical loading (Iwaniec & Turner 2017). Mechanical loading is discussed succinctly with Wolff's Law, which postulates that repetitive loading of bone (for example a sit-to-stand motion), will cause adaptive responses to allow the bone to better carry the load (Teichtahl et al. 2015). This implies a direct correlation between physiological features of the bones and the body mass of an individual, which research has attempted to quantify.

A study conducted utilized 191 samples of both male and female sex with differing ages, weights, and heights. The analysis of diffuse idiopathic skeletal hyperostosis (DISH)—a form of spinal arthritis—osteoarthritis of the tibia, and external dimensions of the femur showed varying levels of association with obesity. In females, there was a positive correlation between both DISH and osteoarthritis with obesity. The regression analysis performed found significance between BMI and all ten tested variables, with a final 78.48% accuracy for females and 84.37% for males (St. George 2008). This study indicates a correlation between components of the skeleton and body mass, as well as provides support for the biomechanical model of study, which attempts to understand the effects of the mass of the skeleton.

However, another study aimed at determining best practices for estimation of body mass found differing results. In this study, femoral head breadth and bi-iliac breadth were used to extrapolate BMI. A sample of 64 individuals was assessed and the accuracy of BMI estimation was determined. The results showed that differences between estimated and actual body mass ranged from -14kg/30lbs to 25kg/55lbs, with negative values indicating lower estimated values than actual body mass. Most values came within 10-20% of the actual value, with correct predictions occurring at less than 50%. This study arrived at the conclusion that the methods utilized were not suitable for estimating BMI of an individual (Jeanson et al. 2017).

Both studies utilized external factors of the lower-limb long bones, specifically that of the femur. Furthermore, both looked at measurements regarding the head of the femur. The head of the femur connects with the pelvis and allows for motion of the leg. It was with these values that greater significance was noticed in each study, implying that joint spaces may be more indicative of body mass. Utilizing joint surfaces in addition to other external measurements may therefore be the most accurate way to estimate body mass.

A separate study, utilizing a different angle, looked to ascertain the relationship between body mass in adults and articular and diaphyseal remodeling of the proximal femur. Within the study, radiographs from 80 living subjects were taken and proximal femoral dimensions obtained. The results suggested that while articular size does not change due to pressure from mechanical loading, the diaphyseal surfaces do exhibit change. This change occurs in the cross-sectional dimensions of the bone. From this, body weight prediction equations gave a roughly 10-16% error rate (Ruff et al. 1991). This indicates, that while both surfaces discussed have valuable data, diaphyseal surfaces may be more indicative of adult body mass and in turn can lead to approximations of body mass, albeit not exactly. As discussed prior, however, even the slightest knowledge of body mass can be useful when dealing with unidentified remains. While this study states that there are no changes in the articular surface, this is stated in changes in response to change in weight. Therefore, the articular surface analyzed outside of the changes in weight by living subjects may provide even deeper insight and allow for better prediction of static weight.

Body Mass and the Joints

Wolff's Law affects skeletal measurements, specifically in regards to joint surfaces. A joint, defined as where two or more cartilage-surfaced bones meet, allow for range of motion and flexibility. The primary weight-bearing joints, which allow for standing and carrying of the body, include those located at the ankles, knees, and hips (Simkin 2018). The impact of motion is most noticed on the head of two of the long bones (the tibia and femur) in the lower limbs. Therefore, most research is concentrated on the impact of weight on the joints of the lower limbs.

For example, several studies have been conducted in analysis of the factors influencing the load-bearing capacity and qualities of the proximal femur head. Since mechanical properties are closely related to bone density, many factors intrinsically affect how much mass the bone can physically hold. The size and shape of the bone tissue both relate to the load-bearing capacity of the femoral head (Morgan & Bouxsein 2008). If these qualities can be quantified, it may provide insight into how much mass an individual could physically bear, providing a closer estimation of body mass.

Research has also been devoted to analyzing the effects of obesity on joints besides that of the femoral head while still focusing on the lower limb. One such study was dedicated to the changes in the surfaces of the knee joint, comprised of the femur and tibia. Twenty-one measurements were collected across a sample size of 162 sets of skeletal remains. This study found that there was a statistically significant difference between measurements collected from normal and obese samples. There was a general trend in secular changes of the knee joint, and indication of obesity as a factor. However, the researchers ultimately determined that these results were inconclusive as to the level of impact obesity had on the presented changes (Harrington 2013).

Limitations in the studies conducted pose an issue for the use of similar methodology for estimation of body mass. Primarily, measurements are only taken from the lower limbs. It is known that the humerus is not a weight-bearing structure in the same manner that the leg is, making analysis via Wolff's Law less likely if looking solely at body mass. However, muscle use and size have been positively correlated with bone size (Edwards et al. 2014), especially when comparing sedentary versus active lifestyles. A correlation between muscle and bone size was observed at the $p<0.001$ level in a sample size of 318 women with varying lifestyles (Edwards et al. 2014). This indicates that while BMI may not directly influence the bone dimensions, factors affecting BMI (such as lifestyle and activity) do affect the dimensions. Looking at this from a forensic standpoint, unidentified remains are not always recovered in their entirety—the upper limbs and torso may be all that is available to investigators for a plethora of reasons. Further research is needed to fully indicate the effect of obesity, undernutrition, and body mass on the skeleton in order to be able to accurately estimate body mass from skeletal remains.

CHAPTER III: MATERIALS AND METHODS

This section will discuss the materials and methods utilized in completion of the research. Materials discussed include the data utilized to select samples for measurement, where samples were obtained, and the sample pool itself. The methods discussed are the skeletal measurement techniques utilized for data collection and the subsequent statistical analysis of the data.

Materials

The research conducted utilized skeletal remains from the University of Tennessee Knoxville (UTK) Donated Skeletal Collection within the Forensic Anthropology Center. All remains are donated either by the individual prior to their death or by next of kin after death has occurred, and a series of policies guides the donation process (https://fac.utk.edu/utk-donated-skeletal-collection/). The remains to be evaluated in this study were requested to be male, below the age of 80 at time of death, and of varying body masses. Upon arrival at the facilities, a list of forty individuals was provided that fit these criteria. All were also identified as being White.

From the supplied list, 20 individuals were chosen for analysis based on a variety of factors. Individuals were excluded if their remains were unavailable at the time research was conducted, such as if they were being utilized by other researchers at the time. Individuals were also excluded if there was damage to the long bones that would interfere with the goals of the study.

A complete list of individuals and their age, stature, weight at death, and calculated BMI is included below in Table 1. Age, stature (in inches), and weight (in pounds) at death were reported by UTK; BMI was calculated using the standard equation of weight (lb) / [height (in)]^2 x 703. For confidentiality purposes, the identification number provided below was created independently of the UTK identification system. Identification number is in the format number/#A-D, with the number indicating the year of donation and the letter indicating the order in which remains donated within the same year were classified.

Table 1—Age, stature, weight, and BMI of individuals in study sample

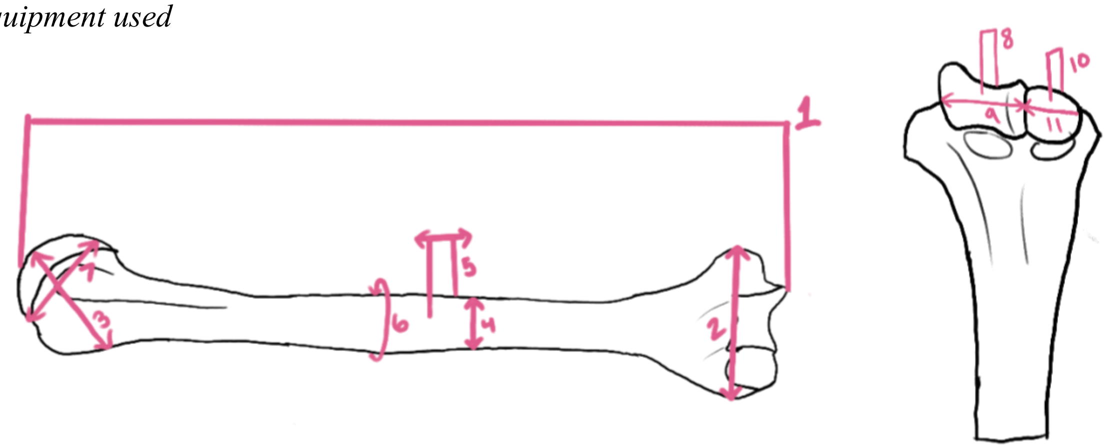
Identification #	Age	Stature (in)	Weight (lbs)	BMI
05A	61	71	150	20.9
08A	63	67	190	29.8
08B	61	72.83	132	17.5
09A	54	68	84	12.8
09B	69	69	200	34.3
10A	43	69	200	29.5
11A	32	72	175	23.7
11B	24	70	150	21.5
11C	54	67	170	26.6
12A	57	69	200	29.5
12B	35	75	245	30.6
12C	67	74	283	36.3
12D	30	69	143	21.1
14A	68	69	205	30.3
14B	48	66	300	48.4
15A	42	74	175	22.5
15B	65	73	300	39.6
16A	63	75	220	27.5
16B	55	69	170	25.1
18A	68	73	222	29.3

Methods

Skeletal Measurements

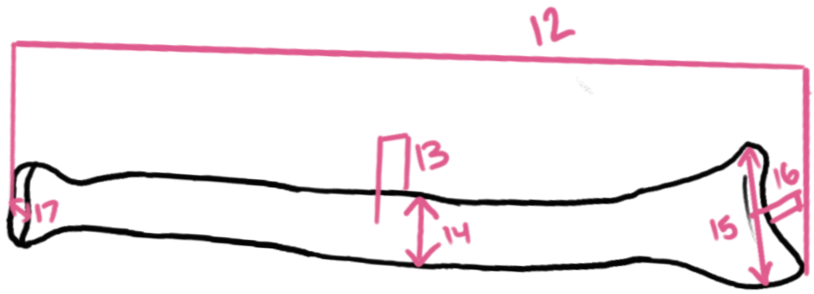
The long bones utilized were the humerus, radius, ulna, femur, and tibia. These were chosen both based on literature describing the weight bearing long bones of the lower leg and based on inclusion of the upper limbs. Skeletal measurements taken included those analyzed in earlier studies (Buikstra & Ubelaker 1994; Harrington 2013), but several new ones were created for this study to better reflect joint area in the upper limb. The measurements are briefly described in Figures 1-5.3; equipment used is also given. All measurements were sourced from Buikstra & Ubelaker 1994 unless otherwise notated. When measuring, each set of remains was unpackaged from the box individually, all measurements taken, and the bones replaced in the box before the next set of remains were examined. All data was recorded in an Excel spreadsheet. Following all measurements for all sets of remains being taken, intra-observer error was assessed by retaking measurements of three randomly chosen individuals. The dataset can be viewed in full in Appendixes A-C.

Figures 1 and 1.1—Descriptions of measurements of humerus (anterior view) and equipment used



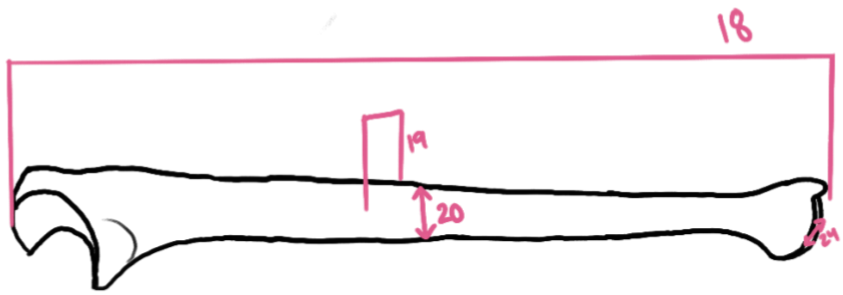
1. Maximum Length; soft tape measure
2. Epiphyseal Breadth; digital sliding caliper
3. Vertical Diameter of the Head; digital sliding caliper
4. Maximum Diameter at Midshaft; digital sliding caliper
5. Minimum Diameter at Midshaft; digital sliding caliper
6. Circumference at Midshaft; digital sliding caliper
7. Horizontal Diameter of the Head (created for study); digital sliding caliper
8. Thickness Trochlear Joint Surface (created for study); digital sliding caliper
9. Breadth Trochlear Joint Surface (created for study); digital sliding caliper
10. Breadth Capitular Surface (created for study); digital sliding caliper
11. Thickness Capitulum Surface (created for study); digital sliding caliper

Figure 2—Descriptions of measurements of radius (anterior view) and equipment used



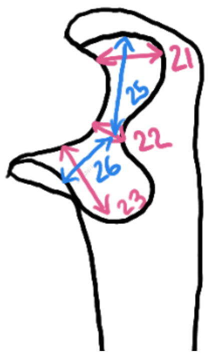
12. Maximum Length; soft tape measure
13. Anterior-Posterior (AP) Diameter at the Midshaft; digital sliding caliper
14. Medial-Lateral (ML) Diameter at the Midshaft; digital sliding caliper
15. Maximum Length of Distal Joint Surface; digital sliding caliper
16. Maximum Breadth of Distal Joint Surface; digital sliding caliper
17. Maximum Diameter of the Head (created for study); digital sliding caliper

Figure 3.1—Descriptions of measurements of ulna (anterior view) and equipment used



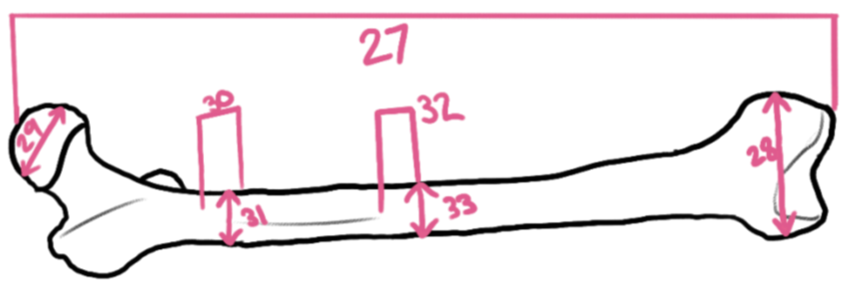
18. Maximum Length; soft tape measure
19. AP Diameter at the Midshaft; digital sliding caliper
20. ML Diameter at the Midshaft; digital sliding caliper

Figure 3.2—Descriptions of measurements of ulnar superior joint surfaces (anterior view) and equipment used



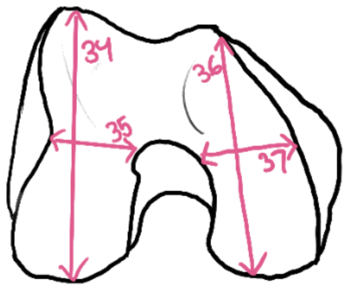
21. Superior Head Diameter (created for study); digital sliding caliper
22. Medial Head Diameter (created for study); digital sliding caliper
23. Inferior Head Diameter (created for study); digital sliding caliper
24. See figure 3.1; Distal Head Diameter (created for study); digital sliding caliper
25. Olecranon Superior Surface (created for study); digital sliding caliper
26. Olecranon Inferior Surface (created for study); digital sliding caliper

Figure 4.1—Descriptions of measurements of the femur (anterior view) and equipment used



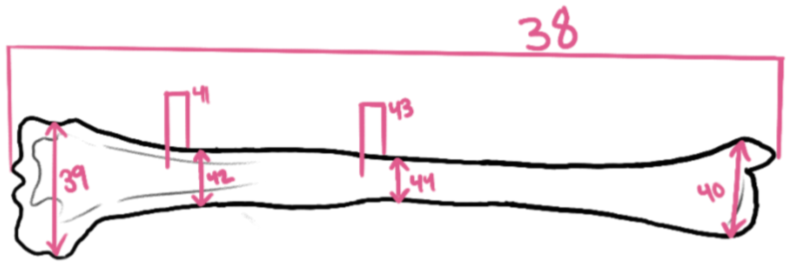
27. Bicondylar Length; soft tape measure
28. Epiphyseal Breadth; digital sliding caliper
29. Maximum Diameter of the Head; digital sliding caliper
30. AP Subtrochanteric Diameter; digital sliding caliper
31. ML Subtrochanteric Diameter; digital sliding caliper
32. AP Diameter at the Midshaft; digital sliding caliper
33. ML Diameter at the Midshaft: digital sliding caliper

Figure 4.2—Descriptions of measurements of the femur (inferior view) and equipment used



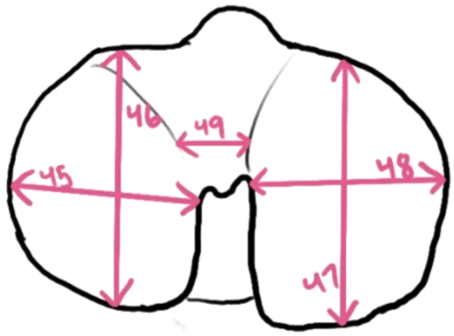
34. AP Lateral Condyle Diameter (created for study); digital sliding caliper
35. ML Lateral Condyle Diameter (created for study); digital sliding caliper
36. AP Medial Condyle Diameter (created for study); digital sliding caliper
37. ML Medial Condyle Diameter (created for study); digital sliding caliper

Figure 5.1—Descriptions of measurements of the tibia (anterior view) and equipment used



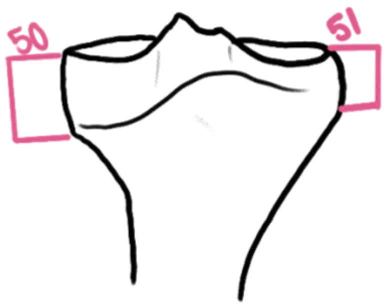
38. Maximum Length ; soft tape measure
39. Maximum Proximal Epiphyseal Breadth; digital sliding caliper
40. Maximum Distal Epiphyseal Breadth; digital sliding caliper
41. Maximum Diameter at Nutrient Foramen; digital sliding caliper
42. ML Diameter at Nutrient Foramen; digital sliding caliper
43. AP Diameter at Midshaft; digital sliding caliper
44. ML Diameter at Midshaft; digital sliding caliper

Figure 5.2—Descriptions of measurements of the tibia (superior view) and instruments used



45. AP Lateral Condyle Diameter (created for study); digital sliding caliper
46. ML Lateral Condyle Diameter (created for study); digital sliding caliper
47. AP Medial Condyle Diameter (created for study); digital sliding caliper
48. ML Medial Condyle Diameter (created for study); digital sliding caliper
49. Intertubercle Distance (Harrington 2013); digital sliding caliper

Figure 5.3—Descriptions of measurements of the tibia (posterior view) and equipment used



50. Posterio-lateral Epiphyseal Thickness (Harrington 2013); digital sliding caliper
51. Posterio-medial Epiphyseal Thickness (Harrington 2013); digital sliding caliper

Two additional variables were created for this study from the collected data. To better analyze the correlation between body mass and the joints in the upper arm, variables indicative of joint surface areas were created. Utilizing the humeral distal joint breadth and distal joint thickness, a variable was calculated for the area of the humeral distal joint surface. This process was repeated with the radial distal joint surface. These variables were included in the following analysis.

Statistical Analysis

To conduct statistical analysis, the software SPSS Statistics (version 29.0.0.0), developed by IBM, was utilized. Descriptive analysis consisting of the minimums, maximums, means, and standard deviations was run on all measured variables as well as BMI values for each sample. Following this, a Pearson correlation analysis was conducted between each skeletal measurement variable, including the joint surface area variables, and the BMI values. A P-value of 0.100 was utilized given the exploratory nature of the research and the small sample size involved.

The materials and methods discussed in this chapter were developed in order to accurately determine the correlation, if any, between body mass and skeletal measurements of the long bones. All analysis run by SPSS was interpreted and evaluated for significance. The correlation values calculated, as well as other trends in data, are discussed in the following chapter.

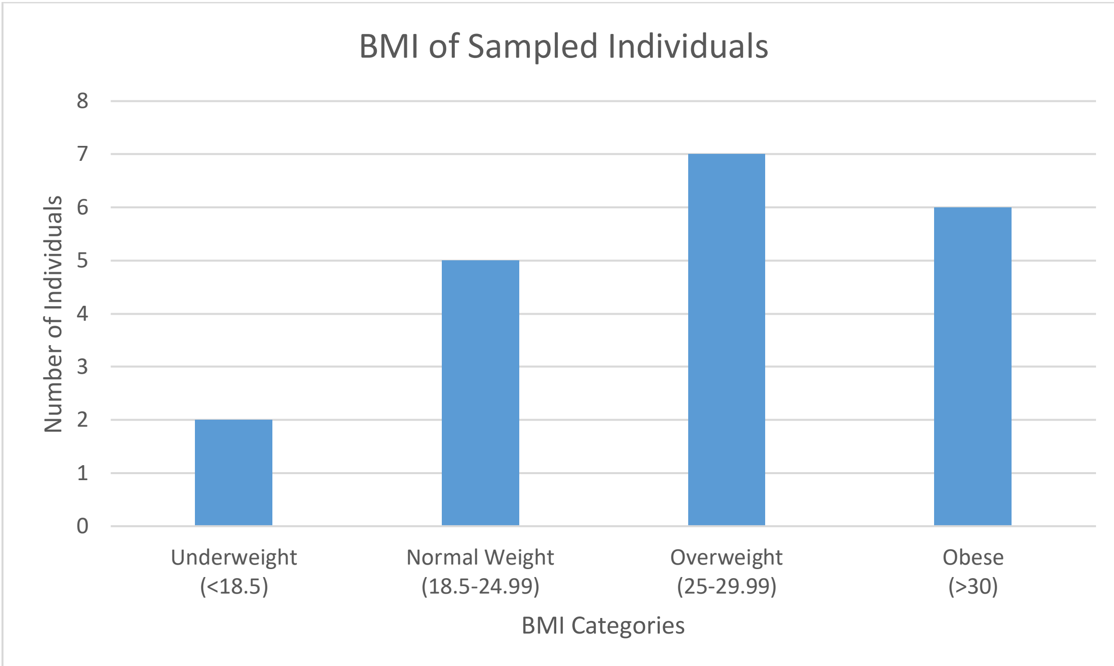
CHAPTER IV: RESULTS

In this chapter, the results produced from metric analysis of the sample of 20 makes of varying BMIs are presented. They are broken into three categories: sample characteristics, analysis of diaphyseal surface dimensions, and analysis of articular surfaces. Each section breaks down the collected datasets further and points out significance where necessary. Discussion of results can be found in the following chapter. Significance was determined utilizing a P-value of 0.100.

Sample Characteristics

Using SPSS, comparison was made between several variables and recent data in the United States to test to what degree it presented a representative sample of the U.S. population. The median age of the samples was 56, which is higher than the median age of the American population, which is approximately 38.8 as of 2021 (United States Census Bureau). The BMI of the sample population ranged from 12.8 (underweight) to 48.4 (obese) (Figure 6). The average BMI for the sample population was 27.84. Comparatively, the average BMI for an adult male in the United States is 29.4 (National Center for Health Statistics 2021). Both of these values fit into the classification of overweight, though the sampled individuals' average BMI skews lower than the national average. These differences in age and BMI are likely a reflection of the smaller sample size and even more that the sample is composed entirely of deceased individuals. Thus, the study sample is not wholly representative of the American population, but it is still reflective of the trends of BMI in the United States.

Figure 6—BMI distribution of sample individuals by category



In the analysis of intraobserver differences, the mean error rate among the measurements for all three individuals was found to be 1.63%.

Analysis of Diaphyseal Dimensions and BMI

Following this, the skeletal measurements taken from the diaphysis of each bone were analyzed for the mean, standard deviation (SD), and range, as well as for their correlation with BMI. These results are shown below, separated by the bone the measurements were taken from. The intra-observer error for all measurements taken was calculated utilizing three re-measured samples.

Diaphyseal Measurements of the Upper Limb and BMI

As seen in Tables 2-4, two variables were found to have significant positive correlation with BMI. Both variables occurred at the midshaft of the humerus, which is by far the largest and thickest of the arm bones considered. No other correlations were apparent, even for midshaft dimensions of the lower arm bones. Surprisingly, some correlations were discovered to be negative, which is surprising given that such correlations are extremely rare in the skeleton due to the pattern of growth exhibited by humans. Furthermore, although the coefficients were all very low, all involved maximum bone lengths.

Table 2—Measurements of the humeral diaphyseal surface: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Maximum Length	328.92	24.15	111.37	-.105	.660
Max. Diam. at Midshaft	23.87	2	7.82	.433*	.057
Min. Diam. at Midshaft	19.05	2.27	10.47	.415*	.069
Circumference at Midshaft	70	4.10	14.53	.180	.448

*Significant at p<0.10

Table 3—Measurements of the radial diaphyseal surface: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Max. Length	251.38	11.54	38.45	-.070	.769
AP Diam. at Midshaft	12.28	.92	2.98	.204	.388
ML Diam. at Midshaft	16.06	1.30	4.92	.137	.564

*Significant at p<0.10

Table 4—Measurements of the ulnar diaphyseal surface: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Max. Length	270.97	11.62	47.62	-.231	.326
AP Diam. at Midshaft	12.76	1.14	4.48	.185	.435
ML Diam. at Midshaft	17.13	1.04	3.42	.224	.343

Diaphyseal Measurements of the Lower Limb and BMI

The measurements of the lower limb show higher correlations with BMI than do the upper limb measurements. Four show significance at the 0.10 level and two of these are significant still at the 0.05 level. These measurements largely occur in the tibia, and again all variables involve midshaft diameters (Table 6). Also similar to results seen in the arm, all correlations between bone length and BMI were negative, although again none were statistically significant.

Table 5—Measurements of the femoral diaphyseal surface: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Bicondylar Length	463.26	13.73	38.54	-.255	.278
AP Subtrochanteric Diam.	30.15	2.32	8.57	.168	.480
ML Subtrochanteric Diam.	35.89	3.35	11.43	.247	.293
AP Diam. at Midshaft	30.81	2.11	9.55	.230	.330
ML Diam. at Midshaft	28.02	2.90	9.07	.488*	.029

*Significant at $p<0.10$

Table 6—Measurements of the tibial diaphyseal surface: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Max. Length	396.29	16.11	61.53	-.200	.399
Max. Diam. at Nutrient Foramen	36.37	2.60	8.93	.274	.243
AP Diam. at Nutrient Foramen	25.10	2.59	9.30	.500*	.025
AP Diam. at Midshaft	30.21	3.17	13.92	.441*	.051
ML Diam. at Midshaft	22.29	1.86	6.54	.442*	.051

*Significant at $p<0.10$

Analysis of Articular Surface Dimensions and BMI

Following this, the skeletal measurements taken from the articular surfaces of each bone were also analyzed for the mean, standard deviation (SD), and range, as well as for their correlation with BMI. These results are shown below, separated by the bone the measurements were taken from.

Articular Surface Measurements of the Upper Limb and BMI

Similar to the diaphyseal measurements, the articular surfaces of the upper limbs showed little statistically significant correlations with BMI (Tables 7-9). Only two variables, breadth of capitular surface of radius and maximum breadth of distal articular surface of the ulna, reached significance, and no pattern was seen between them as was observed with the midshaft diameters of the long bones. showing significance.

Table 7—Measurements of the humeral articular surfaces: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Epiphyseal Breadth	64.16	3.66	13.79	.360	.120
Vertical Diam. of Head	42.69	5.01	18.91	.101	.672
Horizontal Diam. of Head	45.47	2.73	11.56	.232	.326
Thickness of Trochlear Joint Surface	17.41	1.29	5.25	.021	.931
Breadth of Trochlear Joint Surface	25.34	1.67	6.72	.238	.311
Breadth of Capitular Surface	18.93	2.88	8.93	.426*	.061
Thickness of Capitular Surface	27.89	2.16	8.57	.257	.274
Distal Joint Surface Area	1946.88	305.41	1186.02	.174	.462

*Significant at $p<0.10$

Table 8—Measurements of the radial articular surfaces: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Max. Length Distal Joint Surface	34.29	2.21	8.66	.205	.386
Max. Breadth Distal Joint Surface	22.69	1.54	5.69	.393*	.087

Table 8—Continued

Max. Diameter of Head	23.46	1.69	6.22	.100	.674
Distal Joint Surface Area	779/64	87.03	315.08	.203	.391

*Significant at p<0.10

Table 9—Measurements of the ulnar articular surfaces: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Superior Head Diam.	25.52	1.91	7.28	.166	.483
Medial Head Diam.	20.92	1.82	6.21	.058	.809
Inferior Head Diam.	26.23	2.68	11.64	.035	.884
Distal Head Diam.	17.04	2.01	8.96	.128	.592
Olecranon Superior Surface	17.75	1.61	6.22	-.055	.818
Olecranon Inferior Surface	15.47	1.71	7.51	-.044	.854

*Significant at p<0.10

Articular Surface Measurements of the Lower Limb and BMI

Similar to the diaphyseal measurements of the lower limb, there was greater correlation with BMI in the articular surface dimensions of the leg as compared to those of the arm. This is apparent in Table 10, where four measurements showed significance at the 0.10 level. For the femur, three variables were located on the distal end and all included the M-L aspect of the joint surface; the other significant correlation was seen in the proximal diameter of the tibia, which also participates in the M-L aspect of the knee joint (Table 11). However, as also seen in Table 11, several measurements of the tibia exhibited negative correlation, although again no pattern among them was evident.

Table 10—Measurements of the femoral articular surfaces: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Max. Diam. of Head	47.99	2.39	8.62	.225	.339
Epiphyseal Breadth	83.17	4.64	15.77	.507*	.023
AP Lateral Distal Condyle Diam.	63.68	3.63	14.79	.083	.729
ML Lateral Distal Condyle Diam.	32.08	2.96	9.67	.586*	.007
AP Medial Condyle Diam.	58.89	5.79	25.15	.337	.145
ML Medial Condyle Diam.	28/05	3.60	13.80	.521*	.019

*Significant at p<0.10

Table 11—Measurements of the tibial articular surfaces: descriptive analysis and correlation with BMI

Measurement	Mean	SD	Range	Correlation with BMI	P-Value of Correlation
Max. Proximal Epiphyseal Breadth	78.78	4.14	13.71	.428*	.060
AP Lateral Prox. Condyle Diam.	43.49	3.35	13.01	-.023	.925
ML Lateral Prox. Condyle Diam.	34.82	2.49	10.56	.178	.452
AP Medial Prox. Condyle Diam.	49.23	3.01	12.03	-.099	.678

Table 11—Continued

ML Medial Prox. Condyle Diam.	34.97	3.48	13.49	.301	.197
Intertubercle Distance	9.34	2.34	9.85	-.326	.161
Posteriolateral Epiphyseal Thickness	17.22	4.13	14.61	-.251	.285
Posteriomedial Epiphyseal Thickness	20.06	2.14	8.01	.286	.222
Max. Distal Epiphyseal Breadth	51.67	3.25	10.48	.073	.760

*Significant at $p<0.10$

The significant variables indicate a positive correlation between BMI and skeletal measurements. Graphs below show the trend of best fit for all variables found significant at or below the 0.05 level, i.e., those showing the strongest correlations (Figures 7-11). As may be seen, while a positive trend is exhibited, the values are well scattered about the regression line. There is a slight pattern in the correlations for the femoral midshaft M-L diameter (Figure 8) and the tibial nutrient foramen M-L diameter (Figure 10) for individuals with lower BMIs to fall below the regression line and those with higher BMIs to fall above the line. These findings indicate a slight trend that those with lower BMI values tend to fall below values predicted by the metric variable involved and those with higher BMI values fall above predicted value, showing further support, although admittedly limited, for the differences in body size being reflected. However, it must be noted that for the individual with the highest BMI of the sample, the data from this individual consistently falls below the regression line, suggesting the bone diameters were much smaller than would be expected; no explanation is apparent.

Figure 7—Individual's BMI plotted against values for the epiphyseal breadth of the femur

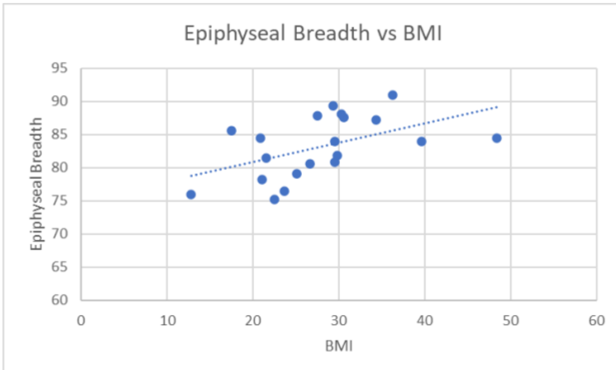


Figure 8—Individual's BMI plotted against values for the medial-lateral diameter at the midshaft of the femur

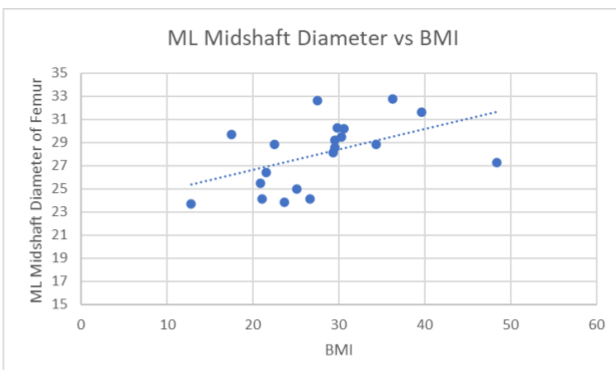


Figure 9—Individual's BMI plotted against values for the anterior-posterior diameter of the medial condyle of the femur

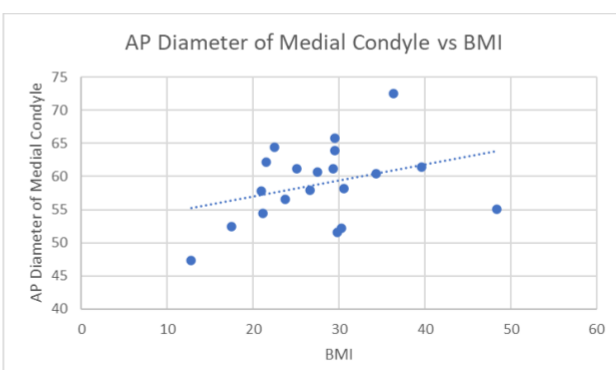


Figure 10—Individual's BMI plotted against values for the medial-lateral diameter at the nutrient foramen of the tibia

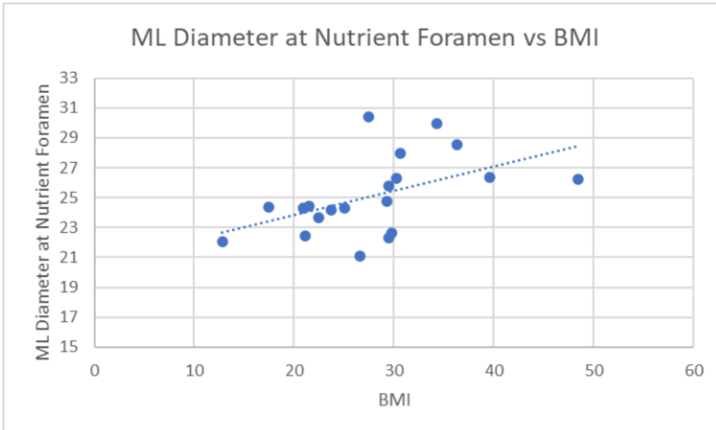
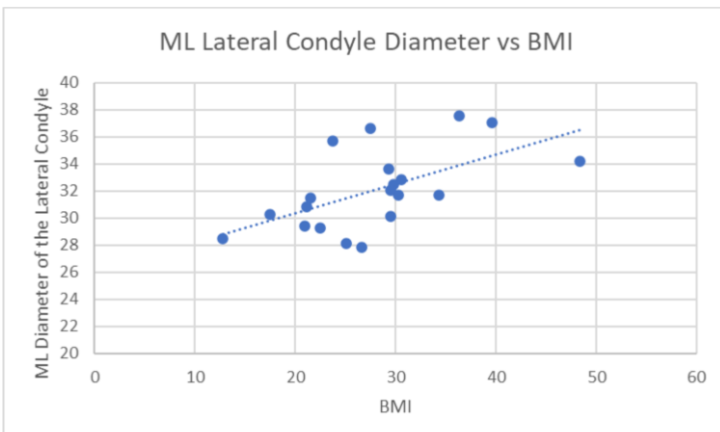


Figure 11—Individual's BMI plotted against values for the medial-lateral diameter of the lateral condyle of the femur



The null hypothesis, H_0, was partially upheld. While there was some significance shown in correlation between body mass and skeletal measurements, the significance was only noted in a few values.

The following alternate hypotheses were observed and supported by these results:

H_1: There is significant correlation between body mass and articular surface size of the long bones.

H_{1a} The correlation is present in both the long bones of the upper and lower limbs, but stronger in the lower limbs.

There is evidence for positive correlation between body mass and articular surface size, especially in the lower limb. More variables that were statistically significant were found in the knee joint as compared to the hip. Only two significant correlations were seen in the elbow joint surface dimensions.

H_2: There is a significant correlation between body mass and diaphyseal diameters of the long bones.

H_{2a}: The correlation is present in both the long bones of the upper and lower limbs, but stronger in the lower limbs.

While correlation was present in both upper and lower limbs, it was seen more strongly in the lower limb. The midshaft diameters of the humerus, tibia, and femur support this hypothesis, while the diameters for the radius and ulna did not.

CHAPTER V: DISCUSSION

Out of the 53 measured measurements taken on the joint surfaces and diaphyseal portions of five long bones, 12 were found to be significantly correlated with BMI. These variables were found in both the upper and lower limbs, though majority were found in the lower limbs. The variables found to be significant were located on both of the articular and diaphyseal diameters of the bones. However, there were far fewer significant variables than expected, even at the 0.10 level. While fewer variables were shown to be significant than expected, this is reflective of previous literature in which the use of skeletal measurements were used in conjunction with body weight prediction equations to predict mass. These equations predicted body mass with a 10-16% error rate, which indicates that skeletal measurements, while significant, may not be the most refined indicators body mass (Ruff et al. 1991).

Notable to the significance of variables is the location from which they were taken. Again, most of the significant measurements occurred in the lower leg. This is crucial, as the lower leg, and the knee in particular, plays a critical role in weight-bearing mechanisms in the lower limbs. Previous studies utilized Wolff's Law, which states that joints change in response to the stress put upon them, to illustrate that obesity can disproportionately affect the tibiofemoral compartment (Teichtahl et al. 2015). In another study, the size of the tibiofemoral compartment, where the femur and tibia are connected to form the knee joint, has been positively correlated ($r=0.63$, $P< 0.005$) with movement levels in adults, as well as with body mass (Jackson et al. 2004). In the present study, this same pattern is reflected in the articular surfaces of the femur as noted in Table 10 and the articular surfaces of the tibia in Table 11. Specifically, this dynamic is observed in the epiphyseal breadth of the femur and the epiphyseal breadth of the tibia, both which were found to be statistically significant.

Diaphyseal measurements showing significance largely occurred within the tibia, although significance was also seen in the femur and humerus. Other research has also shown a positive correlation between body mass and tibial bone area. A study aimed at determining the effects of knee-adduction movement on the tibial bone area found a positive correlation between the two, indicating a relationship between movement at the knee and the tibia (Creaby et al. 2010). This is reflected in this study via Table 6 and Figure 10, which shows slight correlation between diaphyseal dimensions and BMI. Again, it was expected that there would be significance in the lower limbs, especially in the knee joint, since it is a primary weight-bearing joint in the human body.

A surprising result is the lack of significance in dimensions associated with the hip joint, which also is a primary weight-bearing joint. Body mass estimation from the skeleton largely utilizes femoral head diameters (Pomeroy et al. 2019), yet this study found no significant correlation between BMI and the femoral head diameters. A study utilizing x-ray scans of 155 young adults determined that while the femoral head can predict mass, it is an association found strongest in young adults and does not account for differences between muscle and fat mass (Pomeroy et al. 2019). This is reflected in a second study, where femoral measurements were taken to determine the accuracy of body mass estimation techniques, although the femoral head was found to be less correlated than the other variables tested, such as biepicondylar breadth (Chevalier 2018). Thus, it was somewhat unexpected in this research that femoral head diameter was found to be non-significantly correlated with BMI; it may be related to the fact that joint size, rather than bone morphology directly, was evaluated.

As was mentioned earlier in the literature review, relatively little research has been conducted concerning the ability of the upper limb bones to predict BMI. Therefore, one of the goals of this study was to explore their effectiveness. Again, the humeral midshaft dimensions did show significant correlation with BMI. However. another study comparing the cross-sectional areas of both the humerus and femur (non-weight-bearing and weight-bearing, respectively) found that while both cross-sectional areas exhibited changes due to age, there were no correlations found between body mass and geometry of the humerus; this was also observed in the present analysis. Furthermore, the study found that changes in the humerus geometry associated with aging were due to muscle use and atrophy rather than changes in general body mass (Allen et al. 2011).

In the upper arm, significant correlations with BMI were also observed at the elbow joint, where the capitulum of the humerus connects with the joint surface of the radius. The breadth of this joint connection and the cross-sectional area of the humerus have both been a focus significance in previous research. A study utilizing 16,494 datapoints obtained through the U.S. Health and Nutritional Examination Survey determined that elbow breadth was correlated with size (referred to as frame) at higher rates than the bitrochanteric breadth in the leg. The researchers involved determined that elbow breadth was therefore an acceptable indicator of frame size (Frisancho & Flegel 1983). However, no other joint surfaces, including the humeral head, were found to be valuable in estimating body size.

Clearly, the results of this study do not support that bone morphology is an absolute indicator of body size. From a forensic standpoint, one must consider the scientific rigor of methods employed, especially if findings will become evidence in court. Most courts today utilize the Daubert criteria (Grady 2006), but it has been suggested that Daubert criteria may disproportionately affect fields such as forensic anthropology, where both objective and subjective methodologies can be employed (Christensen & Crowder 2009). However, body mass estimations would be primarily used only to help narrow down the range of possible identifications for a set of remains, and any final identification entered into legal proceedings would use one of the more accepted methods previously mentioned, such as DNA or dental findings. Nevertheless, body mass estimation itself has been consistently tested for reliability, with recommendations being made as to which techniques have lower error rates, which techniques are best for different BMIs, and other important considerations (Schaffer & Dunn 2017; Auerbach & Ruff 2004). Overall, there appears to be a positive outlook for the general estimation of BMI using skeletal measurements, especially for the leg bones.

CHAPTER VI: CONCLUSION

Five long bones (humerus, radius, ulna, tibia, and femur) were measured across a sample size of twenty males of varying body mass in order to explore their reliability in predicting body size, especially for the arm bones. Fifty-one measurements assessing joint surface area as well as shaft diameters were taken directly from the remains, while three more were extracted from the existing data. These measurements were then analyzed to determine correlation between measurement taken and the BMI of the individual. Based on the findings of this research, it can be concluded that while body mass does influence the skeleton, this influence is best seen in the long bones of the lower limbs, with both the articular and diaphyseal regions exhibiting signs of this influence. In contrast, the skeletal measurements taken from the humerus, radius, and ulna of the individuals did not show a consistent correlation with body size.

The results of this research have the potential to impact several fields and disciplines. The results shown here provide increased literature on the impact of body mass on the human skeleton. This is useful for anthropological research, where determining body mass may have impact on cultural studies (Schug & Goldman 2014). An understanding of a historical group's body mass may provide important insight into their lifestyle and habits, which can in turn increase our understanding of cultures of the past. The results may also provide insight for medical professionals on the clinical effects of obesity and weight on the body (Cao 2011). Understanding these effects will allow for diagnostic practices that can take into account the impact weight changes (such as from medication) may impact the body. Most aligned with the goal of this study is the impact these results may have on the field of forensic science, specifically that of forensic identification. This research indicates that the lower limbs may exhibit enough correlation that a BMI could be approximated, resulting in the narrowing of possible identification matches. As discussed in the review of literature, even approximation of a characteristic may aid in the identification process. This research, while not to be used as a sole means of identification, adds to the breadth of knowledge already existing on methods of identification.

There were a few notable limitations for the study. Most impactful is that of the sample size. A larger sample size would likely provide more reliable findings concerning the impact of body mass on the skeleton. This would allow for closer analysis of the correlations between the two variables, as well as decreasing the possible margin of error. Another limitation was the use of technology. Digital calipers were used for this study, which is consistent with practices in the field of anthropology. However, computer programs that allow for three-dimensional mapping of the bone could provide increased accuracy and precision and may alleviate part of the human error that may have been encountered during the study (Sindhu & Soundarapandian 2019; Oka et al. 2009). These programs are generally expensive and require substantial knowledge to use, making them often impractical for studies such as this.

Future research should focus on expanding the breadth of knowledge surrounding the effects of body mass on the lower limbs. This research should include a larger sample size and may choose to utilize a sample of differing ancestry and sex, rather than a demographically similar sample. Doing so would decrease the chance that correlation is due to one of these demographic characteristics rather than to the body mass alone. There is also the potential for exploring how different lifestyles affect body mass (for example, level of athleticism) affect skeletal measurements. Further research could also explore whether or not the muscle attachment sites located on these joints exhibit influence on joint size—this could be done alongside the previously mentioned expansions of the study. Finally, there is opportunity to explore how accurately the BMI of an individual can be predicted utilizing the measurements taken during this study and other similar research. As discussed in the literature review, this is an angle that has been explored previously, but further knowledge is necessary to adequately asses the scope of the practice.

APPENDIX A: MEASUREMENTS TAKEN FROM SAMPLES 5A-11A

	5A	8A	8B	9A	9B	10A	11A
Humerus							
1	342.73	338.32	341.77	337.56	332.58	323.83	349.85
2	64.37	62.4	65.49	58.99	63.44	65.77	58.66
3	45.66	41.82	42.65	35.58	43.64	43.23	41.91
4	23.82	22.91	24.39	19.82	23.5	26.21	20.27
5	22.8	19.5	19.52	17.74	18.98	20.28	15.24
6	73.69	74.5	74.95	61.7	73.71	74.21	60.42
7	46.63	43.11	45.58	44.82	48.2	47.08	41.68
8	18.4	15.68	18.04	17.57	16.84	16.71	14.37
9	27.51	24.51	24.98	23.19	26.48	24.71	22.65
10	19.32	16.67	16.47	15.01	19.69	17.79	14.82
11	24.69	27.64	27.3	24.26	28.3	25.33	25.95
Radius							
12	258.28	250.52	261.41	228.7	253.38	246.03	255.03
13	12.06	11.72	13.21	10.7	13.38	13.14	11.38
14	15.98	14.58	16.91	13.73	15.5	16.69	13.9
15	35.65	32.09	35.44	30.72	34.26	33.18	29.75
16	22.39	21.05	23.21	20.06	22.32	22.4	24.35
17	21.02	22.29	23.8	22.74	24.67	23.98	22.1
Ulna							
18	272.06	266.26	283.5	254.47	268.18	270	282.91
19	11.81	12.76	14.73	11.62	12.79	12.23	12.3
20	16.7	16.71	18.76	16.82	16.33	16.98	18.14
21	24.36	23.77	28.11	23.16	27.37	26.8	21.61
22	19.05	20.66	22.43	21.23	22.44	23.15	20.34
23	27.09	26.48	28.1	21.77	25.7	24.96	25.87
24	18.31	15.76	15.06	15.37	16.77	17.56	15.27
25	17.06	18.33	20.22	18.77	19.36	17.53	15.34
26	14.32	14.49	15.89	15.32	15.68	14.94	12.84

APPENDIX A CONT. : MEASUREMENTS TAKEN FROM SAMPLES 5A-11A

Femur	5A	8A	8B	9A	9B	10A	11A
27	484.9	460.26	484.09	459.15	452.5	459.51	460.32
28	84.44	81.91	85.65	75.92	87.18	83.95	76.52
29	49.86	45.18	52.32	46.37	50.55	47.19	43.7
30	28.87	30.82	30.32	30.03	34.6	29.13	26.03
31	33.04	39.43	36.95	32.24	42.33	35.8	34.64
32	31.56	32.65	30.08	28.62	31.46	28.71	24.91
33	25.52	30.29	29.73	23.71	28.83	28.58	23.85
34	66.45	67.07	65.01	62.1	63.87	63.73	56.64
35	29.42	32.5	30.27	28.51	31.71	32.09	35.69
36	57.81	51.61	52.46	47.35	60.48	63.99	56.56
37	23.81	26.42	28.46	24.75	30.75	28.1	25.06
Tibia							
38	391.43	395.47	405.27	387.1	397.1	385.07	405.07
39	78.97	79.03	79.96	74.84	84.9	77.63	72.43
40	47.13	53.12	57.23	49.06	53.46	48.82	49.02
41	34.65	34.32	33.64	34.44	38.33	34.05	33.33
42	24.32	22.63	24.36	22.08	29.98	25.76	24.16
43	31.51	30.66	28.06	25.14	28.56	29.41	22.24
44	23.24	20.63	23.37	20.79	24.79	23.4	19.75
45	44.62	45.32	45.92	39.15	41.17	43.66	42.94
46	36.17	38.95	35.04	35.1	36.56	33.84	35.13
47	46.35	52.57	50.54	45.7	48.7	49.53	46.28
48	31.94	36.29	31.35	31.66	40.93	36.92	33.4
49	9.27	6.38	13.01	14.14	4.29	8.58	7.06
50	12.84	17.78	12.34	17.92	9.52	17.04	23.29
51	21.14	18.69	17.06	19	21.57	21.49	20.21

APPENDIX B: MEASUREMENTS TAKEN FROM SAMPLES 11B-14A

	11B	11C	12A	12B	12C	12D	14A
Humerus							
1	355.21	330.57	338.83	329.97	328.28	307.85	307.34
2	63.67	59.94	65.86	67.71	71.25	62.16	66.2
3	49.65	43.2	41.99	54.12	51.55	40.31	41.42
4	24.41	21.17	24.87	24.75	24.64	24.14	24.6
5	16.84	17.7	18.69	18.28	18.74	17.26	20.72
6	71.67	66.47	70.42	71.26	71.54	71.08	73.38
7	45.59	42.74	43.13	44.82	53.24	42.39	48.02
8	17.59	17.66	17.67	19.33	19.62	15.97	18.95
9	24.69	25.38	25.65	27.91	27.02	24.74	21.19
10	18.04	16.76	15.39	20.62	22.85	18.21	23.49
11	29.33	28.19	32.83	24.6	29.99	29.38	29.72
Radius							
12	264.67	237.31	257.05	256.42	265.95	239.34	239.39
13	11.77	11.87	12.85	12.31	13.68	11.53	12.14
14	17.51	14.74	17.07	15.6	14.91	15.54	18.65
15	32.95	34.22	35.71	37.05	37.18	33.12	36.21
16	21.25	22.53	24.02	22.69	23.71	20.03	25.72
17	23.51	20.4	24.31	24.92	24.34	22.11	26.35
Ulna							
18	291.21	255.82	278.07	277.94	280.54	258.22	263.89
19	11.85	11.32	11.87	13.42	15.8	12	14.31
20	16.18	16.66	15.62	17.49	18.03	15.57	18.99
21	24.8	24.34	24.45	28.89	25.47	23.99	25.13
22	19.91	18.82	20.06	23.78	17.88	19.02	22.15
23	32.47	24.65	26.22	28.99	25.51	20.83	22.3
24	18.91	18.22	16.46	19.73	22.37	15.76	16.85
25	17.45	16.67	21.56	19.51	16.41	16.13	19.4
26	14.89	15.58	16.58	17.26	14.21	14.5	15.56

APPENDIX B CONT. : MEASUREMENTS TAKEN FROM SAMPLES 11B-14A

Femur	11B	11C	12A	12B	12C	12D	14A
27	481.17	448.56	478.24	455.92	481.52	447.69	450.68
28	81.5	80.54	80.83	87.61	91.01	78.25	88.08
29	48.1	44.73	46.92	49.61	50.52	45.11	49.15
30	29.33	27.37	32.01	28.4	30.76	26.91	31.53
31	31.05	30.9	37.47	33.27	34.5	36.25	40.27
32	30.37	28.8	31.84	30.96	32.61	29.24	33.15
33	26.41	24.12	29.2	30.22	32.78	24.11	29.5
34	64.06	64.13	67.51	57.72	71.43	58.29	67.5
35	31.5	27.85	30.15	32.87	37.52	30.87	31.67
36	62.17	57.95	65.82	58.23	72.5	54.47	52.24
37	25.42	25.63	29.6	32.28	37.61	26.41	24.55
Tibia		=					
38	410.03	365.59	403.02	399.68	390.46	376.83	389.16
39	75.59	74.04	76.83	80.57	86.14	73.53	78.58
40	49.78	52.25	55.47	53.34	57.61	50.04	51.43
41	37.07	33.03	38.22	40.83	37.92	35.07	38.11
42	24.42	21.1	22.3	27.96	28.56	22.45	26.3
43	30.27	27.41	33.38	34.04	36.16	29.22	33.59
44	22.6	18.25	21.1	23.98	24.73	19.43	24.03
45	43.51	42.46	46.42	45.44	44.37	38.44	40.3
46	33.12	28.39	37.58	31.56	33.7	31.27	33.94
47	49.35	47.93	54.12	51.81	47.24	50.79	49.64
48	33.42	29.85	32.07	36.46	36.62	32.95	35.76
49	11.3	9.51	6.89	11.1	9.56	7.56	12.03
50	14.1	23.16	16.14	20.2	14.89	22.25	15.76
51	18.18	19.68	24.91	23.09	22.13	16.9	20.04

APPENDIX C: MEASUREMENTS TAKEN FROM SAMPLES 14B-18A

	14B	15A	15B	16A	16B	18A
Humerus						
1	307.74	243.84	334.39	343.81	334.71	349.17
2	61.78	67.41	69.76	64.45	57.46	66.35
3	41.2	42.23	36.73	45.75	35.96	35.21
4	23.56	22.74	27.64	26.52	21.88	25.56
5	19.79	17.02	25.71	18.86	17.4	19.85
6	67.29	68.67	70.93	65.69	67.29	71.24
7	44.87	45.37	43.86	48.98	43.34	45.94
8	16.06	17.28	17.63	17.16	16.91	18.82
9	25.66	26.44	25.35	26.21	25.15	27.36
10	18.35	18.03	21.7	23.75	17.99	23.55
11	27.43	28.23	28.12	30.17	27.29	29.07
Radius						
12	227.5	247.95	256.44	264.08	260.12	258.04
13	11.39	10.8	13.61	12.1	12.37	13.5
14	15.72	17.77	17.22	15.94	16.68	16.56
15	32.09	34.88	35.7	38.41	33.48	33.75
16	20.4	22.46	23.74	23.43	24.33	23.77
17	21.22	23.17	25.27	23.93	22.49	26.62
Ulna						
18	243.59	273.08	275.78	282.5	268.79	272.66
19	11.87	12.73	13.24	12.64	13.51	12.41
20	17.39	16.57	18.79	15.74	17.69	17.41
21	23.69	26.96	27.92	27.29	25.99	26.39
22	18.74	19.54	24.09	22.45	20.49	22.15
23	25.4	27.68	27.36	25.9	28.68	28.57
24	13.41	15.71	18.65	15.4	17.41	17.76
25	17.38	17.62	16.81	17.42	16.27	15.84
26	11.69	14.65	19.2	16.7	17.67	17.33

APPENDIX C CONT. : MEASUREMENTS TAKEN FROM SAMPLES 14B-18A

Femur	14B	15A	15B	16A	16B	18A
27	446.36	459.36	459.87	460.05	449.94	484.83
28	84.45	75.24	84.03	87.8	79.16	89.33
29	48.17	46.7	49.58	50.16	45.71	50.34
30	27.1	3104	33.22	33.9	30.58	31.1
31	33.63	33.92	36.91	42.19	34.87	38.28
32	29.88	31.79	30.77	34.46	32.51	31.88
33	27.3	28.86	31.65	32.63	25.02	28.14
34	60.61	66.34	63.57	61.72	63.78	62.11
35	34.19	29.28	37.08	36.64	28.12	33.65
36	55.09	64.45	61.39	60.7	61.24	61.21
37	27.55	26.89	33.85	31.94	25.61	26.35
Tibia						
38	363.01	417.93	416.95	424.54	396.46	405.54
39	75.72	75.43	85.18	83.75	79.03	83.45
40	47.26	50.61	50.83	49.57	49.8	57.49
41	33.87	34.77	38.32	41.96	36.7	38.82
42	26.21	23.69	26.34	30.4	24.32	24.74
43	29.58	30.17	32.41	32.12	28.87	31.31
44	23.48	22.75	23.94	22.51	20.82	22.11
45	39.64	42.23	41.74	51.45	41.14	49.82
46	35.45	34.62	37.37	37.95	35.79	34.96
47	43.07	51.37	50.01	48.86	45.68	55.1
48	31.08	35.58	37.78	43.34	33.68	38.4
49	10.35	8.61	8.46	8.76	9.57	10.32
50	12.14	15.65	16.82	24.13	21.59	16.76
51	18.03	20.18	21.12	17.14	18.81	21.84

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